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MECHANICAL DESIGN AND OPTIMIZATION OF SWARM-CAPABLE UAV LAUNCH SYSTEMS

by

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June 2015

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This research is an exploration of the mechanical design and optimization of swarm-capable UAV launchers. Fully autonomous swarms are predicted to play a significant role in the future of war fighting, but the capability is currently limited by deficiencies in supporting technologies. Effectively launching a swarm of UAVs requires a departure from existing solutions due to the unique logistical and operational requirements specific to this use-case. This study highlights the systems engineering processes used to provide a solution that met all cost, schedule, and performance requirements for the stakeholders. The end result was the successful development and demonstration of a launching system prototype specifically developed to rapidly launch a high number of UAVs to support the swarming mission.

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MECHANICAL DESIGN AND OPTIMIZATION OF SWARM-CAPABLE UAV LAUNCH SYSTEMS

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ABSTRACT

This research is an exploration of the mechanical design and optimization of swarm-capable UAV launchers. Fully autonomous swarms are predicted to play a significant role in the future of war fighting, but the capability is currently limited by deficiencies in supporting technologies. Effectively launching a swarm of UAVs requires a departure from existing solutions due to the unique logistical and operational requirements specific to this use-case. This study highlights the systems engineering processes used to provide a solution that met all cost, schedule, and performance requirements for the stakeholders. The end result was the successful development and demonstration of a launching system prototype specifically developed to rapidly launch a high number of UAVs to support the swarming mission.

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List of Acronyms and Abbreviations

AMPPS Automated Multi-Plane Propulsion System

ANSI American National Standards Institute

AoA analysis of alternatives

ARSENL Advanced Robotic Systems Engineering Laboratory

BDA battle damage assessment

CAD computer-aided design

CBA capability-based assessment

CONOPS Concept of Operations

COTS commercial, off-the-shelf

CRUSER Consortium for Robotics and Unmanned Systems Education and Research

DAG Defense Acquisition Guidebook

DOD Department of Defense

ELINT electronic intelligence

EW electronic warfare

GCS ground control station

ICD Initial Capabilities Document

ISR intelligence, surveillance, and reconnaissance

JATO jet-assisted take-off

JCA Joint Capability Area

JCIDS Joint Capabilities Integration and Development System

KPP Key Performance Parameter

MALD Miniature Air-Launched Decoy

MAV micro aerial vehicle

MOE measures of effectiveness

MOP measures of performance

NPS Naval Postgraduate School

OTH-T over-the-horizon targeting

POC proof-of-concept

POW prisoner of war

RATO rocket-assisted take-off

RFID radio-frequency identification

ROS Robot Operating System

RSTA reconnaissance/surveillance/target acquisition

RULE Rapid UAV Launch Engine

SAR search and rescue

SAR synthetic aperture radar

SE systems engineering

SEAD suppression of enemy air defenses

TAF terminal area forcast

TRL Technical Readiness Level

UAS unmanned aerial system

UAV unmanned aerial vehicle

UHMW ultra-high-molecular-weight polyethylene

VTOL vertical take-off and landing

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Executive Summary

This research is an examination of the mechanical design and optimization of rapid-cycle UAV launchers to support the swarming UAV mission. UAV launching systems currently available lack many of the capabilities required to execute the swarming mission. Specifically, they lack the ability to rapidly reset in order to launch a high number of UAVs in a short period of time. Contained within is the design methodology and testing results of one of the first existing prototypes of a launching system specifically developed for rapidly launching a large number of UAVs to support the swarming UAV mission.

The research goal is to design and build a working UAV launcher prototype that meets all cost, schedule, and performance requirements for the Advanced Robotic Systems Engineering Laboratory (ARSENL) team. From beginning to end, systems engineering (SE) practices are utilized as the framework. The core benefit afforded through the use of SE is that it provides the necessary tools and techniques to make informed decisions throughout the process. Multiple SE models exist, but for this research, the desire is to adhere to the DOD guidelines as prescribed in the Defense Acquisition Guidebook (DAG), Chapter 4 [1]. The guide lends itself well to developmental systems like the one in this study, and it also adheres to the accepted terminology prevalent in existing DOD acquisition programs. An overview of this process is shown in Figure 1.

The methodical approach to system decomposition afforded by this method allows the engineer to fully define a set of requirements that satisfy the operational needs of the stakeholders. This process is essential to product development because it defines precisely what the prototype must "do" to provide value to the stakeholders. In complex systems, it is easy to inadvertently overlook requirements that, if omitted, would render the solution useless. The decomposition process is used to holistically evaluate a total system solution in order to minimize the likelihood of this occurring. An overview of the top-level requirements found during this process is listed below:

R1 The system shall be capable of launching 50 aircraft within 15 minutes.

R2 The system shall be configured such that a maximum number of two technicians are able to setup the launcher in 15 minutes or fewer.

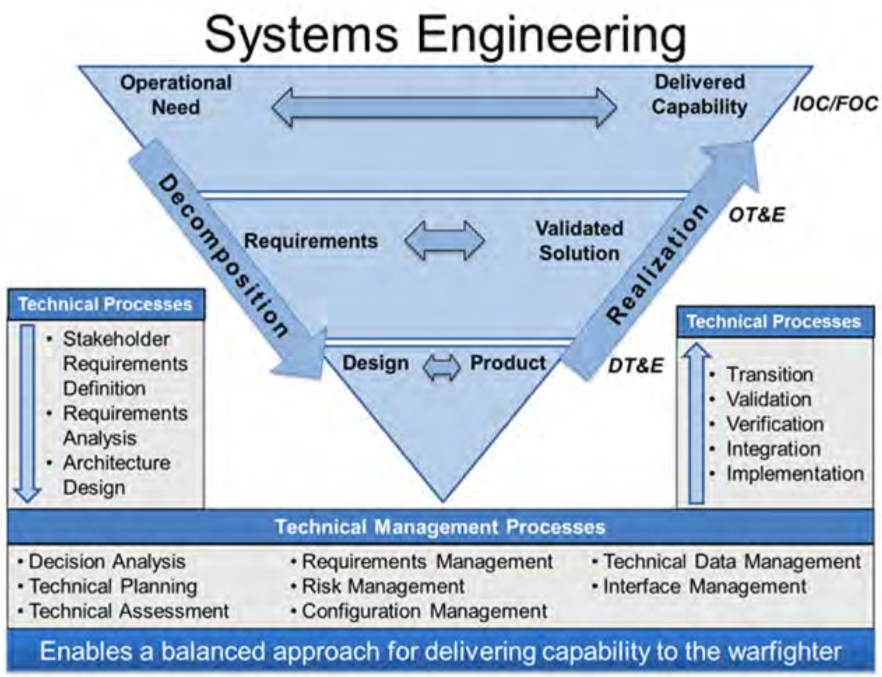

Figure 1: DOD SE Process Overview, from [1]

R3 The system shall demonstrate a failure-to-launch rate of less than or equal to one percent.

R4 The system shall be capable of reorienting 90 degrees in less than or equal to 15 seconds.

R5 The system shall provide a means of alerting the user to system status and potentially unsafe operations.

R6 The system shall not require an alteration of the UAV in such a way as to make it unusable with the legacy launcher system.

R7 The system shall utilize no more than five custom components.

R8 The system shall be shorter than 16 feet to accommodate transportation in ARSENL's trailer.

R9 The prototype developmental costs shall not exceed $10,000.

Once an understanding of the system requirements is established, a market analysis determines if an existing system is capable of meeting said requirements. Also, this process aids in the identification of industry design standards that could be applied to the developmental phase of research. Results indicated that the market had not yet responded to the swarming use-case, and a unique solution was warranted; therefore, the process transitioned to concept development.

Concept generation and design selection was accomplished through the evaluation of the proposed system against stated requirements and build feasibility. The limited manufacturing and construction capabilities of the two-man development team had to be accounted for when selecting a concept. Based on these considerations, a belt-driven, electrically-powered solution was selected. The concept shown in Figure 2 is based on the principle of baseball pitching machines that utilize compression to accelerate and eject the baseball.

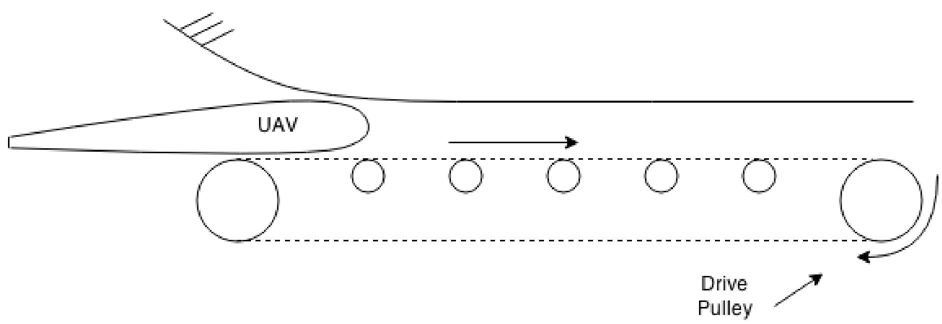

Figure 2: Side View of Single Motor Pitching Machine Concept

Following concept development, design goals were established and evaluated using DOD TRL definitions. Also, a risk management plan was generated to help determine the correct order for technological progression. High-risk, critical systems were developed first, followed by the integration of less essential sub-systems. The progressive introduction of technology was accomplished through iterative prototyping. This development method allows for rapid design changes to both address current issues, and mitigate future risk concerns. The proof-of-concept (POC) developed during this phase of research is a rolling chain launcher assembly that utilizes a 3-D printed interface to connect to the chain during launch. Attachment of the UAV is accomplished through the use of industrial, double-mushroom Velcro. The launch technician needs only to position the aircraft, and apply light downward pressure to engage the Velcro. At the completion of a launch stroke, the drive sprocket redirects the chain around its circumference, thereby breaking the Velcro bond with the UAV. For power, a four-cell, 48-volt battery array provides 250 amps of current to a permanent magnet, DC 10.75 HP motor. An overview of the POC is shown in Figure 3.

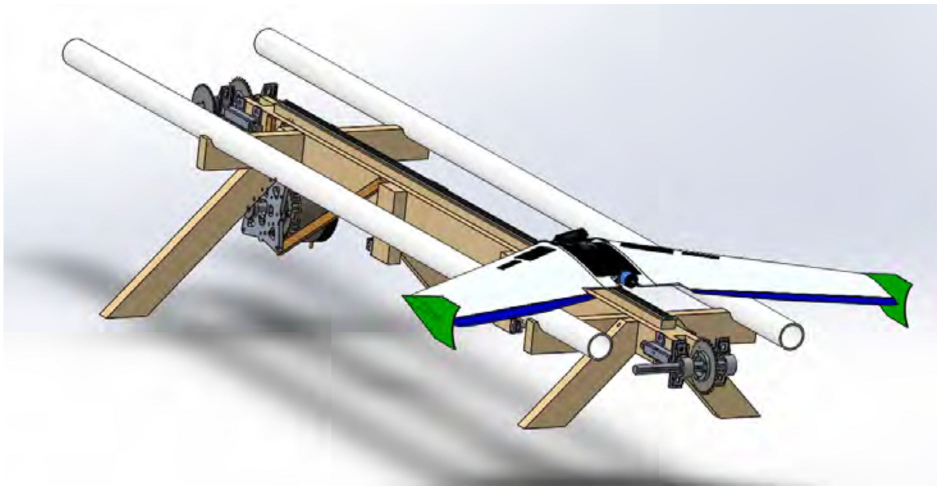

Figure 3: POC Overview with UAV

Throughout the prototyping process, the suitability of the system was continuously assessed. This was accomplished using a series of developmental tests and evaluations (DT&E). The purpose of this type of testing is to determine the current TRL of the prototype, and update the status of perceived risks as they evolve. Also, the tests are used to verify that the design solution is meeting system requirements. Once the concept was validated, significant investments were made into developing a metalized prototype with automated systems and advanced sensing capabilities. The prototype is named after the high-current draw required for launch and is shown in Figure 4.

Figure 4: AMPPS System Prior to Launch

At the completion of prototype construction, the final stages of DT&E were conducted at the ARSENL testing facility. The AMPPS solution either met, or is predicted to meet, all requirements established at the beginning of the design process.

Table 1: AMPPS Prototype Specifications

AMPPS Prototype	
Weight	245 Pounds
Length	12 Feet
Width	32 Inches
Launch Velocity	38 MPH
Reset Time	4 Seconds

An abbreviated table of specifications for the Automated Multi-Plane Propulsion System (AMPPS) prototype is shown in Table 1. The launcher is at a TRL of six, and technological risks are minimal. Also, the solution was delivered on time and under budget. The success of the system is directly attributed to the team's adherence to using established SE practices from research conception to completion.

List of References

[1] DAU, "Defense Acquisition Guidebook," Tech. Rep. 1, 2011. [Online]. Available: https://dag.dau.mil

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dedication to making it a team effort.

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CHAPTER 1:
Introduction

This thesis is an examination of the mechanical design and optimization of rapid-cycle unmanned aerial vehicle (UAV) launchers. UAV launching systems currently available lack many of the capabilities required to execute the swarming mission. Contained within is the design methodology and testing results of one of the first existing prototypes of a launching system specifically developed for the swarming mission. Swarm-capable UAV systems represent the apex of airborne autonomy, and are likely to play a significant role in the future of unmanned air power [1], [2]. Supporting systems that enable this emergent technology are likely to hold valuable strategic and monetary stakes in the UAV market for both defense and private industries. The Teal Group, an aerospace and defense market analysis firm, recently projected annual UAV spending to nearly double from $6.4 billion to $11.5 billion over the next 10 years [3]. The summation of this estimate accumulates to $91 billion by 2024 [3]. If the Teal Group is correct, there is an immediate need for support equipment that enables the future of UAV mission capability growth.

To fully illustrate the basis for this design, it is important first to examine a brief history of UAV development. The historical study of UAV capability growth provides valuable insight into the benefits afforded through swarming UAV missions.

1.1 Early UAV History

Many consider UAVs to be a relatively new development in aircraft technology; however, the general concept originated several hundred years ago, shortly after the 1783 invention of the balloon [4]. In 1818, Charles Rogier suggested, in a treatise, that enemy harbors be attacked by bombardment from unmanned, rocket-carrying balloons [4]. This was presented as an alternative to the time-period convention of land or sea-born attacks. Though not immediately implemented, an adaptation of his idea occurred several years later, in 1849, when Austria launched unmanned, bomb-carrying balloons against Venice [5]. Though not very effective, this attack marked the first historical occurrence of aerial bombing [6]. Also, if one relaxes the current Department of Defense (DOD) definition of a UAV that requires the aircraft to be controlled, it can be reasonably deduced that this was also the first use of UAVs for aerial bombing [7]. Despite Austria's rudimentary execution and marginal impact, the same concept of aerial bombing was the premise that fueled the United States' entry into UAV development.

The first UAV built in the U.S. would not be possible until 1912 when the Sperry Gyroscope Company developed an automatic control system for the Curtiss Flying Boat [8]. This system, dubbed the "Sperry Aeroplane Stabilizer," was created to help mitigate the inherent instability found in early aircraft designs [8]. Although the initial intention was to reduce pilot workload during flight, its future implementations would prove far more versatile. As was the case with many emergent technologies during that time, the impending U.S. entry into World War I would rapidly propel the interest in developing military applications for commercial products. Sperry's autopilot was no exception. Using the Curtis N-9 seaplane as a platform, the Army began conceptual application testing for the world's first autonomously controlled flying bomb [2]. Although the program was riddled with early-phase failures and eventually canceled in 1918, the Army had not lost hope for the flying bomb concept [2]. The contract was transferred to Charles Kettering, who created the "Kettering Bug" and successfully completed an autonomous flight of 40 miles while carrying 180 pounds of explosives [9]. This became the first U.S. example of a recognized UAV system [10].

American development of the UAV and supporting technologies continued as military applications expanded. Sullivan notes that UAV development during this period was more evolutionary than revolutionary, and was largely driven by the advancements in parallel technologies as opposed to directed UAV research [10]. For example, much of the stability and control logic incorporated into UAVs was the result of air-to-air missile developments such as the AIM-9 [10]. As the supporting technology advanced, UAVs evolved from marginally operable flying bombs into highly capable reconnaissance platforms by the 1960s. Cook considers this period the transition point into the modern era of the UAV [2].

1.2 Modern Military UAV Development

The Vietnam War would prove to be a hazardous period for American military pilots and aircrew. From 1964 to 1972, more than 5,000 American airmen perished in downed aircraft

[2]. Additionally, the surviving aircrews who were captured accounted for 90% of the total number of American prisoners of war (POW)s during the Vietnam War [2]. Given the high level of risk to aircrew, the decade-long engagement became a catalyst for modern military UAV development. Unknown to the general public at the time, UAVs documented 3,435 sorties during Vietnam, with some vehicles boasting a 97.3% completion rate for low-altitude, real-time photography missions [9]. In addition to reconnaissance missions, these UAVs were performing battle damage assessment (BDA), electronic intelligence (ELINT) missions, and distributing propaganda leaflets [2]. It is important to note these missions were being accomplished with no risk to human life and at a significantly reduced cost compared to manned aircraft [2]. While this represented a very successful demonstration of military application for UAV use, the missions were considered to be of low strategic risk and non-combative. Because of this, the United States would remain skeptical of the platform's potential to perform in high-stake scenarios or combative missions [2]. It was not until Israel demonstrated the combative capability of UAVs that U.S. military officials became interested in further development.

Beginning in 1978, border conflicts were occurring between Israel and Southern Lebanon [2]. The Lebanese were using SA-6 surface-to-air missiles against Israeli forces who, in response, began using UAVs to overwhelm the Lebanese targeting systems, exhaust their missile supplies, and act as expendable targets to protect the Israeli manned fighters [2] [9]. The UAV defense tactics worked and, despite the several technical and capability deficiencies with the platform – such as an inability to fly at night – the overall outcome proved to the United States that UAVs could "perform valuable, real-time combat service in an operational environment" [9].

After Israel's successful military demonstration, UAV technology began rapidly developing through the late 1980s and into the turn of the century. As interest grew, the supporting technology advanced and, as a result, UAV mission capabilities expanded. The first notable, large scale, U.S. UAV acquisition program revolved around the Israeli-built Pioneer. This platform flew over 300 reconnaissance missions in the Persian Gulf and received high praise for its effectiveness as a reconnaissance/surveillance/target acquisition (RSTA) and over-the-horizon targeting (OTH-T) platform [2], [11]. After the Pioneer, UAV platforms began rapidly emerging. With each new development, capabilities expanded.

Figure 1.1: RQ-2B Pioneer (U.S. Navy), from [13]

Figure 1.2: 20 RQ-4B (Northrop Grumman), from [12]

As new UAV capabilities were introduced, the necessity for advanced autonomy became apparent. Longer loiter times, increased range, and increasingly complex missions made rising logistical requirements a concern. Consider, for example, Northrup Grumman's RQ-4 Global Hawk. The UAV first flew in 1997 and, as its name implied, the system had a global range of 12,000 nautical miles coupled with a 35-hour airborne endurance [12]. Other UAVs followed similar trends in prolonged mission duration, such as General Atomic's 40-hour endurance Predator UAV [2]. Compared to the Pioneer's range and endurance of 100 miles and five hours, the added mission capabilities afforded to these systems was substantial [13]. Even the visual progression shown in Figure 1.1 and Figure 1.2, from what is essentially a sophisticated remote control airplane to the Global Hawk, is telling of the advancements made.

Within ten years from the start of significant UAV development in the United States, UAVs were not only performing the manned aircraft missions in parallel as a force multiplier, but they were also exceeding manned platform capabilities in key performance areas [14]. It was at this time that autonomous capabilities entered a period of exponential growth that was driven out of operational necessity. Figure 1.3 shows the DOD's graphical representation of this growth as published in their 2005 UAV Roadmap report [1].

The period from 1985 (Pioneer) to 1996 (Predator) saw significant advancements in the area of telemetry reporting between the operator and the UAV. If a fault or error occurred onboard the aircraft, this information was relayed back to the operator, who could then

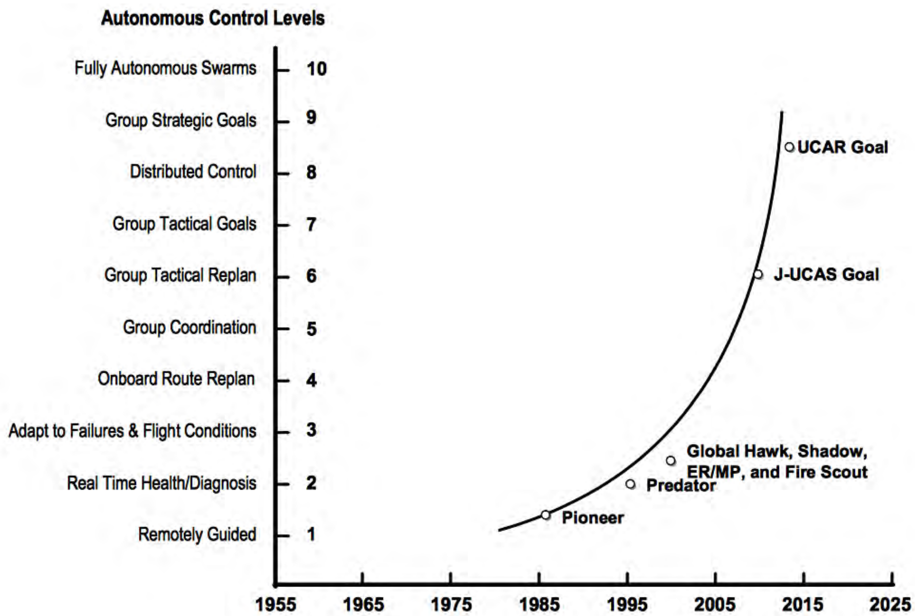

Figure 1.3: Trend in UAV Autonomy, from [1], [2]

make decisions about the appropriate course of action. The functionality was similar to an annunciator panel in modern aircraft that alerts aircrew to a system fault or malfunction. While useful for increasing situational awareness of the system's status, levels one and two of autonomous control were not aimed at removing the human component. They were, however, necessary developments toward this end state. As demands for UAV presence in military operations rose, the operator demands presented a significant sustainment challenge: One of the largest costs in ongoing UAV support is manpower [7]. The then-current system required a large crew to operate one UAV. To satisfy a reduction in both manpower and fiscal resources, the intermediate goal was to achieve a level of autonomy that would allow a single operator to control multiple UAVs [7], [15]. The desired end-state was for UAVs to be self-piloting. The full tactical realization of this capability allows for UAV formations referred to as fully autonomous swarms. Swarming behavior represents the apex of autonomous technology and is shown as *Autonomous Control Level 10* in Figure 1.3. This research is focused on the development of supporting technologies surrounding swarm UAV capabilities; therefore, it is beneficial to review the fundamentals.

1.3 Swarm Overview

Swarming is, at its most basic definition, a decentralized form of cooperative action. It is an exploitation of information sharing between lesser capable units that become more powerful through collaboration. Many authors point to nature as the true origin of swarming behavior [16], [17]. John Arquilla notes that swarm tactics can be seen in the insect colonies of ants and bees, for example [16]. These insects, without direction from a centralized source, are capable of rapidly launching a coordinated attack through the use of swarms. An attack from a single bee or ant is a mere annoyance, but an attack from a swarm of either insect can be deadly. Although a high number of agents are an advantage to swarm attacks, quantity is not what defines a swarm. Rather, it is characterized by the distinctive behavior that swarms demonstrate. The means through which coordination is achieved is what makes swarming unique from other cooperative group actions.

Returning to the example of ants and bees, scientists have yet to identify any sort of DNA code that dictates an order to the insect's swarming behavior [17]. This suggests their observed behavior is emergent and purely reactive based on localized sensing. Clough argues that swarming behavior is implicit; "it just is" [17]. In swarms, there is never a desired result or explicitly-defined outcome; what occurs is never deliberate. This underscores both advantages and disadvantages with swarming behavior.

From a biological viewpoint, one advantage is that swarming species are highly resilient. This characteristic also applies to UAV swarms. Without centralized command, it is difficult for a swarm to be exploited via a "checkmate" type scenario. This characteristic, properly leveraged, presents a notable advantage to the swarm. That stated, there is a limit to how many units may be lost, and that limit, or critical mass, is dependent on the operational goal or mission. For example, one possible use for swarms is a defensive, anti-missile "cloud" being utilized like intelligent chaff. This swarm would continue to be effective so long as the collective density is high enough to be targeted by incoming missiles. If the attack were sufficiently large enough to the extent that a high percentage of sacrificial UAVs were lost, the cloud may cease to be efficacious. However, this is gradual performance degradation. There would not be an instant capability curtailment due to single unit attrition. This is because each unit in the swarm is homogeneous and would not individually possess any sort of critical intelligence driving the outcome. This is important because the species exhibiting swarm behavior in nature are, in general, of low intelligence. Species of higher intellect are capable of planning collaborative efforts to achieve proactive goals. This advantage in perceptual capability usually results in teaming behavior [17]. Teams, unlike swarms, are capable of planning the desired outcome. However, teaming units require higher intelligence than their swarming counterparts.

Implementing a group of autonomous UAVs with teaming tactics would require each unit to have considerable computing power. The resulting UAVs would be arguably superior to a swarm in some aspects, but the expense would be high, and unit loss would therefore be costly. A swarm can accomplish some of the same missions as a team, but for a considerable cost savings. The reduced intelligence requirement for individual units in swarms translates into lower demands on computing power. Intuitively, this translates into smaller, lower-cost solutions for swarming UAVs. With budget concerns at the forefront of conversation in today's politics, any reduction in military spending is well received. For reference, the *2013 Unmanned Systems Integrated Roadmap* brought attention to the fact that "the 2013 Presidential Budget (PB13) [has] reduced the overall DOD budget by $259 billion over the next Future Years Defense Plan (FYDP), with a total reduction of $487 billion over the next 10 years" [7]. It goes on to state that the goal going forward is to develop UAV "capabilities to achieve improved efficiency, effectiveness, and survivability and to reduce the burden on manpower at lower costs while still meeting future operational requirements." Essentially, the desired end-state is to accomplish more with less. A swarming tactical approach is well-tailored to achieving this goal as it does not require the use of costly UAVs. To realize this capability, supporting technologies will need to be developed alongside the basic hardware and software requirements for the UAVs. Of particular interest to this study is the need for swarm-specific solutions to launching these aircraft.

1.4 Launching Considerations for UAV Swarms

As previously discussed, swarming is a group concept that requires significant numbers to function. This presents several unique challenges to launching the UAVs. For one, the time lapse between the first and last unit launched becomes critical. During this period, the swarm is operating at reduced capability. Also, the endurance of each unit comes into play. From the moment the first UAV is initialized, it is consuming energy. Considering there will likely be a holding period while remaining units are launched, this translates to lost range for the swarm. In the case of electrically-powered UAVs where flight times are already limited, this factor becomes even more critical. For a swarm, the launching cycle needs to be expeditious. In order to achieve this, the flow of information and material must be streamlined. For the flow of information, there are two primary categories to consider. The first is audio and/or visual commands between the launch crew. The second is electronic data flow across the launcher's sub-systems.

Time lost during the launching sequence will have a significant, negative impact on the swarming operation. Miscommunication during a swarm launching sequence presents a significant risk to mission success. To mitigate this, standardized communications and crew training are required. Likewise, data transfer delays between the sub-systems will have a similar impact. Any interruption in the data flow will potentially reduce the availability of the launching system. Slow networking will have the same effect.

The flow of material is another aspect to consider. Moving large numbers of aircraft into position will require some level of pre-staging to have them readily available for launch as needed. Automated sensing may be required to help expedite the process. This element of launching a swarm should not be overlooked.

In addition to timing constraints, there are also manpower concerns to take into account. The number of persons required to launch UAVs typically increases with the number of aircraft. One of the key benefits of swarming behavior is the reduced demand on operators and technicians. From a manning perspective, this advantage would be nullified if it required excessive manpower to launch. Great consideration must be taken when designing the human systems interface to minimize the demand on personnel.

To date, launching a UAV has been approached in much the same way as launching manned aircraft. Options include a conventional runway, catapult launch, vertical takeoff, and in the case of lightweight micro aerial vehicles (MAVs), such as those shown in Figure 1.4 and Figure 1.5, hand-launching is also an option.

For swarms, the mission set and the configuration of the UAV are what defines which method of launch is best suited. Short-range swarming missions that do not require high

Figure 1.4: Wasp MAV (AeroVironment), from [18]

Figure 1.5: Black Widow MAV (AeroVironment), from [18]

levels of maneuverability are well-tailored to quad copter-like UAVs. For these vertical take-off and landing (VTOL) aircraft, launching is merely an exercise in adding power. This is convenient, because it does not require prepared surfaces or additional equipment to launch.

Runways are another alternative to launching swarms. They are a convenient launching means as they pre-exist all over the world, and they are already capable of handling high volumes of aircraft. Runways eliminate many reliability concerns because there are not moving parts. The downside is that they require the UAV to have a landing gear, which adds weight and complexity. Also, they are geographically fixed. Operations are not possible outside of the effective swarm radius from the airport facility.

Hand-launching is also a valid approach to launching a swarm as it does not require complex systems and can be accomplished from anywhere a user can stand. However, it only suits a narrow range of UAVs and mission sets. Depending on the size of the swarm, additional personnel may be necessary to complete the launching cycle in order to mitigate operator fatigue. In cases where several hundred or more airborne units are required or needed, hand-launching becomes impractical. Also, this method places a considerable size and weight restriction on the UAV. While they do not have to be as small as the MAVs previously shown, anything over a few pounds will become cumbersome. There are also safety concerns with propellers being in close proximity to the user.

The final option, and the one of interest to this research, is the use of a catapult-type launching system. For the purposes of this study, a launcher will be considered as any system or group of systems external to the UAV that transfers kinetic energy to the aircraft for takeoff. While catapult launchers are usually the most complex solution of the options discussed, they alleviate many of the issues present in the prior alternatives.

- Depending on the design, they can be based on multiple platforms including ships, land vehicles, and even other aircraft.
- Launching systems allow fixed-wing, non-VTOL UAVs to launch without prepared surfaces.
- They are capable of being highly mobile, and are, theoretically, able to safely launch an unlimited number of UAVs.
- UAV launchers are customizable to virtually any mission or UAV platform, making them highly versatile.

CHAPTER 2:
Systems Engineering Approach

Launching systems are available in many forms, and they are frequently customized for specific aircraft platforms and missions. From an engineering perspective, customization is an advantage in that it allows for tailored solutions. However, it is also a disadvantage because there can exist a general lack of continuity in design approach. The one-off nature combined with the newness of the market means it is difficult to capture previous development efforts and systematically evaluate best practices. These challenges were mitigated through the use of an established systems engineering (SE) baseline approach and, when necessary, adaptive methods to complement the uniqueness of the design process.

Systems Engineering is used to ensure "the effective development and delivery of capability through the implementation of a balanced approach with respect to cost, schedule, performance, and risk" [19]. There are multiple valid approaches, and each has its own merits. Approaches are optimized for everything from software design to corporate structure. For this effort, it was desired to adhere to the Department of Defense (DOD) guidelines as prescribed in the Defense Acquisition Guidebook (DAG), Chapter 4 [19]. The guide lends itself well to developmental systems like the one in this study, and it also adheres to the accepted terminology prevalent in existing DOD acquisition programs.

Figure 6.1 shows an adaptation of the inverted V model for SE. The process originates at the top left of the V with a perceived operational need identified by the warfighter. This need is then decomposed into elements that ultimately define the architecture design required to satisfy stakeholder needs. Once materiel solutions are developed or sourced for the product, the realization phase commences with the development and testing of prototypes. The end goal of these tests is to progressively transition, validate, verify, integrate, and implement a product that performs in the desired operational environment prior to delivery. The operational testing phase is intended to test usability and suitability. One should also note the bridge occurring during each phase of realization pointing back to the decomposition side. These continually occurring checks during the product development phase help ensure that identified requirements are being met. Throughout the entire evolution,

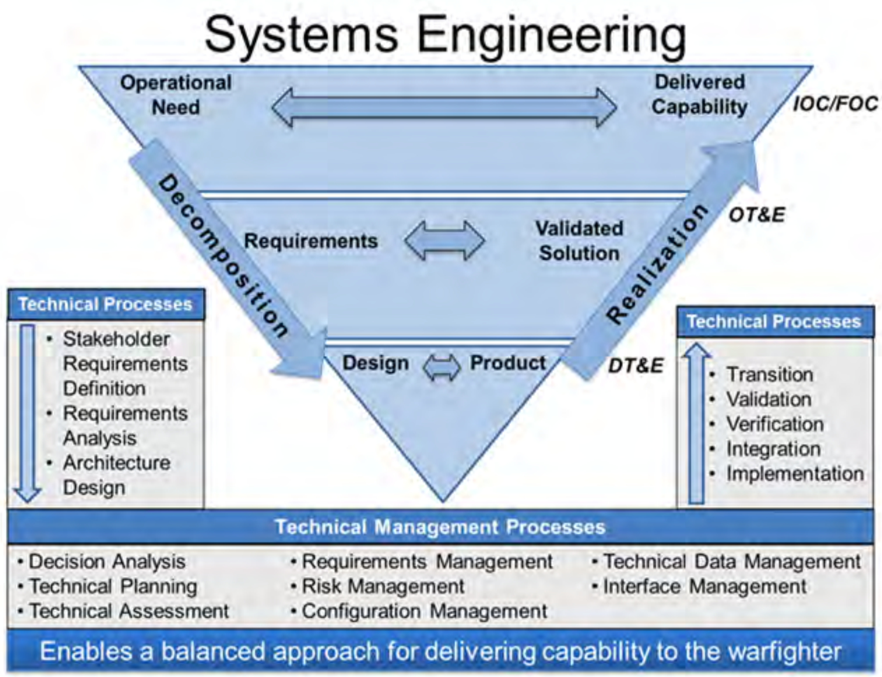

Figure 2.1: DOD SE Process Overview, from [19]

technical management processes are executed.

While this is a baseline for all DOD SE, these processes are scaled and/or modified according to the needs of the design effort. For example, systems of low-complexity with proven technology do not demand the same depth of study when compared to the design of a highly complex, developmental system. This chapter will address the first two elements in the decomposition process: Operational Need and System Requirements.

2.1 Operational Need

Following the SE practices previously outlined, the design effort commenced with building an understanding of the operational needs for the Advanced Robotic Systems Engineering Laboratory (ARSENL).

2.1.1 Problem Definition

This research is in direct support of an operational need defined by the ARSENL lab at Naval Postgraduate School (NPS). However, many of the findings are applicable to other swarming, unmanned aerial vehicle (UAV) systems. The current goal for the ARSENL team is to execute a 50 versus 50 air war using fully autonomous, swarming UAVs. Their chosen airframe is the Zephyr II shown in Figure 2.2.

Figure 2.2: Zephyr II UAV

This is a six-pound, electrically-powered flying wing that is modified to include integrated avionics and advanced sensing capabilities. The airframe and electrical components are, for the most part, well-documented, commercially available items. However, the ARSENL team is at the forefront of utilizing these UAVs in a swarming capacity. This unique application required the team to modify and develop highly complex hardware, software, and human integration solutions.

ARSENL's standing method for launching the Zephyr II aircraft has been the use of a bungee-type system, shown in Figure 2.3. This launching system utilizes a bungee that is anchored approximately 50 feet from a set of PVC launch rails. The bungee is manually retrieved and pulled under tension to the location of the aircraft on the rails. Attachment to the UAV is achieved by sliding a metal ring onto a hook anchored in the underside of the aircraft's wing. A launch crewmember then holds the aircraft under tension until launch is desired and he or she releases the aircraft.

To date, the ARSENL team has used this system to successfully launch 12 aircraft that

Figure 2.3: Zephyr II Launch System

were simultaneously airborne. However, it is incapable of achieving the necessary launch rate to rapidly deploy a mission-capable swarm of 50 UAVs. To satisfy their operational requirements, a different launching solution is required.

2.1.2 Capability Gaps

The first step in the requirement generation process is to identify issues – or capability gaps – in the current solution. To this end, the design team observed ARSENL's operational use of their bungee launching solution and recognized the following list of system deficiencies:

- Operating at a sustainable pace, it took the launch crew between one and 1.5 minutes to retrieve the bungee and reset for launch. If attempting to launch 50 aircraft, the full evolution would consume 50 to 75 minutes. The Zephyr II battery endurance is only 45 minutes, which means that the first aircraft airborne is landing prior to commencement of the swarm mission.
- The launching system requires a minimum crew of two in order to operate: One crewmember to retrieve the launching bungee, and one to position and hold the aircraft while the bungee is attached. The method is labor intensive and impractical for

higher numbers of aircraft. Also, it consumes valuable human assets where automated solutions are viable.

- The crewmember responsible for holdback of the aircraft is in close proximity to the propeller of the UAV. Also, he or she is in the direct path of a highly-tensioned elastic band. Failure of the bungee, its anchor, or inadvertent throttle commands to the UAV presents significant risk to this individual.
- Penetrable ground in which an anchor may be driven is required at the launching site to secure the bungee. Heavy weights of some sort are conceivably viable options when operating off of concrete or hard surfaces, but this has yet to be implemented. Also, the weight required to provide enough frictional holding force would likely be cumbersome to position and relocate. Therefore, a different anchoring method is required to facilitate multi-surface compatibility.
- A shift in the wind direction requires a time-consuming process to re-anchor the bungee and subsequently realign the launch rails. If this were to occur mid-launch cycle, it would effectively scrub the mission. This process must be accelerated and simplified.

Having defined the problem and identified capability gaps in ARSENL's existing launcher technology, the process pivots towards the establishment of requirements.

2.2 System Requirements

Requirements, at the highest level, dictate what the solution must "do" to satisfy the operational needs of the stakeholder. As system decomposition continues below the operational level, more requirements are created that define the necessary system performance and functionality [19]. On a fundamental level, requirements should be traceable, well-defined, and easily measurable. Traceability ensures there is clarity as to why the requirement exists. To promote traceability in this document, requirements are listed at the conclusion of each subsection, linking them to the origin. "Well-defined" implies that there is no ambiguity in what the requirement states. Any reader should clearly understand the statement and threshold value for each requirement. Finally, measurement of requirements is mandated in order to verify and validate the system during testing phases. This enables objective measurements of system success to conclude whether or not the system is performing in accordance with the requirements. These measures are defined in the concluding section of this chapter. The final result of these efforts should be a clear understanding of the system requirements necessary to meet stakeholder's objectives and operational needs. Starting at the highest level, the desires of the stakeholders are analyzed.

2.2.1 Stakeholder Requirement Analysis

Stakeholders are the players who are affected by, or have an interest in, the design project. Usually, stakeholders' needs contradict each other, and this is a tradeoff process where inputs are quantified and scaled to determine the best course of action. However, for a small-scale project with a single customer, the analysis is simplified. Because the ARSENL team was both the customer and the end user with a unified vision for the design, many of the difficulties typical of stakeholder analysis are alleviated. Collectively, the ARSENL team desired the following system characteristics:

- The solution should be capable of the cycle rate required to support 50 aircraft simultaneously airborne with a 30-minute combat endurance.
  - The Zephyr II UAV has an endurance of approximately 45 minutes. This dictates that all aircraft are launched in 15 minutes for the desired combat endurance. This equates to a launch rate of one aircraft every 18 seconds.
- The portability and setup procedure should allow for no more than two technicians to unload and setup the system.
  - If the solution is to be physically lifted out of the trailer, this translates into a weight restriction on the launcher. If the solution exceeds a reasonable lifting threshold, wheel and ramp combinations should be incorporated to accomplish the same end-goal.
- Safety for the user must be ensured.
  - The overall safety of the system encompasses multiple aspects that relate to transportation, setup, and operational concerns. While all are valid and should be addressed, the stakeholder's primary concern is that of operational safety. Launcher systems of any nature involve the rapid transfer of potential energy to kinetic energy. Regardless of how that potential energy is stored, this poses a safety concern to those in the vicinity of the system. It can be likened to a

cocked bow, a pressurized air cylinder, or a tensioned bungee. Each of these examples would require safety measures to ensure user protection should mechanical failure occur. Also, it follows that users should be alerted as to the status of the system. Returning to the example of a pressurized cylinder, visual inspection cannot determine the state of pressurization. This information needs to be communicated to the user so that interactions with the system are appropriate, according to the launcher status. Additionally, system reliability is a determining factor in ensuring user safety.

- The footprint should be minimized for transportation.
  - ARSENL's trailer is 16 feet long, and is also used to transport most of their support equipment, including the UAVs. The launching solution should allow for continued use of this trailer until other factors (such as increasing swarm size) dictate the necessity for a higher volume transportation method.
- Wind shifts should not impact mission success.
  - The reasoning behind this desire was discussed as one of the capability gaps in ARSENL's existing launcher. However, the actual time required to reorient the system was not explicitly stated. For an initial threshold, 15 seconds was considered a reasonable time for the system to undergo a 90-degree reorientation.
- Expenses should be justified for the afforded functionality.
  - There was not an explicit budget stated at the onset of this design effort. When development commenced, estimated costs were reviewed with the stakeholders and approved on a rolling basis. Not long after the development of a proof-of-concept (POC), specific funding was received for $10,000. This became the budget going forward.
- Commercial, off-the-shelf (COTS) components should be utilized to the maximum extent possible.
  - From the viewpoint of the stakeholder, using commercial, off-the-shelf (COTS) components reduces risk, simplifies procurement and maintenance, and has the potential to reduce costs. It does, however, present a challenging integration problem for the design team to harmoniously merge components that were not originally designed to interact.
- The system should be backwards compatible with ARSENL's current launcher. Also,

physical modifications to the UAV are not desired.

  – Developmental systems often take a significant amount of time to fully test and integrate into an existing operation. ARSENL does not want to heavily modify portions of their UAV fleet to accommodate a new launching system. Also, if the system were to fail, backwards compatibility with their existing launcher allows for flight tests to continue.

Stakeholder desires are translated into high-level requirements, or objectives, for the system. These objectives span across multiple categories of requirements, but all are key to high-level system success. Each requirement is categorized and measured at the conclusion of this chapter.

High-Level, Stakeholder Requirements

1. The system shall be capable of launching 50 aircraft within 15 minutes.
2. The system shall be configured such that a maximum number of two technicians are able to setup the launcher in 15 minutes or fewer.
3. The system shall demonstrate a failure-to-launch rate of less than or equal to one percent.
4. The system shall provide a means of alerting the user to system status and potentially unsafe conditions.
5. The system shall be shorter than 16 feet to accommodate transportation in ARSENL's trailer.
6. The system shall be capable of reorienting 90 degrees in less than or equal to 15 seconds.
7. The prototype developmental costs shall not exceed $10,000.
8. The system shall utilize no more than five custom components.
9. The system shall not require an alteration of the UAV in such a way as to make it unusable with the legacy launcher system.

It should be noted that, while this analysis fully represents the primary requirements of the ARSENL team, it is not meant to be a complete documentation of stakeholder design preferences. The design process introduces multiple decision points where alternative selection is brought to the stakeholder for preference.

2.2.2 Scope and Boundaries

It is important to define the boundaries in a system design process to ensure that it is not expanding beyond the solution needed to solve the problem. Likewise, defining the scope ensures the project is not so narrow that it does not fully address the problem. Additionally, there should be an understanding of the various interactions affecting the system. A context diagram is an effective visual tool to aid in all three of these processes.

Observing the context diagram shown in Figure 2.4, the boundaries of the design effort are contained within the central "UAV Launching System" box. The various entities surrounding the central box are not within the scope of this design; however, this does not imply that they are not integral to the system's operation. Each entity must interface with the launcher when either information or material is exchanged.

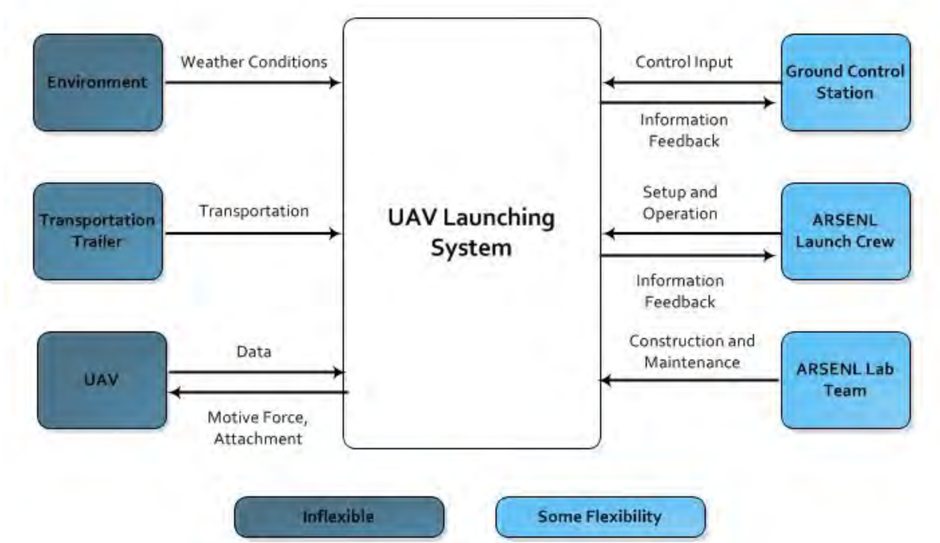

Figure 2.4: Launcher Context Diagram

In some cases, the external entities are inflexible or beyond the control of a design team. The launching environment is an example that falls under this category. For this type of interface, the system must be engineered to the requirements dictated by that interface. Other interactions, such as the interface with the ground control station (GCS), are more flexible. Compatibility is still required for system operation, but the GCS's code or data transfer methods may be modified to suit the launcher's design. For ease of reference, the external systems highlighted in dark blue are considered inflexible. The systems highlighted in light blue represent the more flexible entities. For clarity, a detailed description of each interface follows.

Environment The environment in which the launcher must operate dictates the level of environmental protection that is required of the design. Also, the environment determines the surfaces from which the launcher must be operated. Considerations for environmental conditions such as dust, wind, rain, and temperature should be noted. The ARSENL team currently operates at a UAV testing facility in central California. For this location, there is a significant amount of airborne particulate. This warrants consideration for any contact components such as bearings or slides. Also, electrical equipment may require some form of filtration or barrier where fans are the primary cooling source. When launching aircraft, wind direction relative to the launcher's orientation is a critical variable. Directional shifts in the wind are not uncommon for the testing facility; therefore, it is reasonable to predict that the launcher may require reorientation during a launch sequence. Although the ARSENL team does not currently operate in the rain, it may prove advantageous to provide some level of waterproofing in the event of light, passing showers. Finally, the ambient temperature in this region is moderate; hence overheating or freezing concerns are not predicted to be an issue.

Transportation Trailer Transportation of the launcher is a critical piece to consider because it has a significant impact on usability. The ARSENL team utilizes a 16-foot, enclosed trailer when traveling to and from the launch site. The length of this trailer dictates the maximum allowable length for the launching solution.

UAV The launcher must provide sufficient energy for launch, and transfer that energy to the aircraft. Also, there may be data transfer considerations between the launcher and the UAV. ARSENL's standing procedure is to manually conduct final flight checks with the UAV on the launch rails. With higher rates of launch expected for swarm mission sets, there may be a need for partial or full automation of this process.

GCS The role of the GCS during launch has been rapidly evolving as the team's swarming capability advances. Because of this, the exact level or type of interaction is unknown and will likely evolve over time. However, the current expectation is that communication will between the GCS and the launcher. For this, the launcher will require the ability to send and receive data over the GCS network.

ARSENL Launch Crew The launching crew is the primary consideration for human factors integration. The crew should be highly comfortable interfacing with the design. This dictates that the system is intuitive, safe, reliable, and provides the necessary communication to alert users of safe or unsafe conditions. Also, it should incorporate friendly ergonomics for transportation, setup, and use.

ARSENL Lab Team The ARSENL lab team will be constructing the launcher once it is out of prototype phase. Additionally, they will be responsible for maintenance actions over the lifecycle of the system. A design that utilizes COTS solutions to the maximum extent possible greatly simplifies both processes. Likewise, effort should be given to reducing the number of components that require maintenance and ensuring accessibility for those that do. Last, but perhaps the most important, building a highly reliable system with minimal downtime will greatly benefit this interface.

Intuitively, most of the requirements defined in this subsection are related to system interface compliance. They are shown in the order presented.

Environmental Requirements

1. The system shall be capable of reorienting 90 degrees in less than or equal to 15 seconds. (This requirement is restated for completeness, but it was also stated as a stakeholder requirement.)
2. The system shall be capable of sensing wind speed and direction.
3. The system shall be waterproofed so that light rain showers will not damage any component on the system.
4. The system shall be securable, if needed, to both permeable and non-permeable surfaces.
5. Any components of the system that are subject to degraded performance as a result of airborne particulate shall be sealed.

Transportation Requirements

1. The system shall be shorter than 16 feet to accommodate transportation in ARSENL's trailer. (This requirement is restated for completeness, but it was also stated as a stakeholder requirement.)
2. The system shall be capable of transportation through a standard-width door-

way of 36 inches without disassembly.

UAV Interface Requirements

1. The system shall be capable of providing an aircraft exit velocity of 35 MPH.
2. The system shall be capable of supporting wireless data transfer with the UAV.
3. The system shall provide a method of UAV attachment for the launch cycle.
4. The system shall provide a method of UAV release at the completion of the launch cycle.
5. The force on the UAV's launch hook shall not exceed 20 pounds. (This was the maximum force exerted on the hook by ARSENL's legacy launcher.)

GCS Interface Requirements

1. The system shall be capable of supporting two-way wireless data transfer with GCS.

ARSENL Human Interface Requirements

1. The system shall provide a means of alerting the user to system status and potentially unsafe conditions. (This requirement is restated for completeness, but it was also stated as a stakeholder requirement.)
2. The system shall utilize no more than five custom components. (This requirement is restated for completeness, but it was also stated as a stakeholder requirement.)
3. The system shall demonstrate a failure-to-launch rate of less than or equal to 1 percent.

2.2.3 Operational Scenarios

Operational scenarios are designed to aid in the identification of required system functionality. "An up-to-date Concept of Operations (CONOPS) for the system is basic to understanding the system context, notably mission and task threads and data exchanges that have an impact on the system" [19].

Two scenarios are outlined to present the probable use-cases for the ARSENL team. First, the responsibilities of each team member are reviewed to clarify the scenarios. These roles are changing as capabilities progress, but the descriptions are not expected to differ significantly over the course of system development.

Mission Commander The mission commander is responsible for oversight of the entire testing evolution. This individual coordinates the efforts of the team and offers assistance or guidance where required.

Safety Coordinator This position ensures adherence to safety protocol. To avoid distraction, this individual does not aid in any other processes. Should an unsafe situation develop, it is his or her responsibility to initiate corrective action. All team members share the authority and responsibility to identify and correct unsafe practices, but the coordinator is a fail-safe should any element be overlooked.

GCS Operator This person or persons is monitoring the data link between the aircraft and the GCS. (They) are responsible for conducting pre-flight verification of the UAV's automated systems and ensuring the aircraft are functioning as programmed throughout mission execution. He or she is not always within line-of-sight of the launching location; therefore, communication with launch crews has historically been established via verbal relay.

Swarm Commander The swarm commander monitors the swarm as a whole. His or her responsibility is to monitor and control the swarm's behavior throughout the mission.

Development Engineer This crewmember is available on standby to provide debugging services during the test should data link or software issues arise.

Flight Crew Chief The crew chief oversees all ground operations involving the UAVs. He or she is coordinating the efforts of the aircraft commander, the flight preparation technician, and the launch technician.

Aircraft Commander/Safety Pilot This role is likely temporary, but is currently in place to manually override autopilot inputs should the situation dictate. The aircraft commander closely monitors all aircraft for the first few seconds after launch until the autopilot engages. He or she will then remain on standby throughout the mission.

Flight Preparation Technician This position prepares all UAVs for the mission. This includes coordination with the GCS operators during autopilot initiation, systems check of the aircraft, and pre-staging of the aircraft.

Launch Technician The launch technician is responsible for executing the UAV loading process required for launch. He or she will be directly interacting with the launching platform and transferring aircraft from the staging location to the launcher. This individual is also the final approval authority who commands the system to launch.

If all aircraft are pre-staged for launch, the flight preparation technician will also aid the transference of aircraft.

Scenario One – Single Launcher For this scenario, a single launcher is utilized to launch the entire salvo of swarming UAVs. The launch technician unloads the system, and transports it to the desired launching location. The technician then prepares the launching system for operations by performing whatever setup is required.

Once operational, a series of checks is conducted to ensure proper functionality of the launcher. These checks likely commence with a visual inspection of critical components and one or more dry launches (if feasible) to check mechanical soundness. Depending on the connectivity of the system, data links are confirmed between the GCS and launcher, as well as the launcher and the UAV.

With sound functionality, the flight preparation technician conducts pre-flight checks and UAV staging. Using a single launcher, the pre-stage setup is critical to mission success. All 50 UAVs need to be within reasonable distance of the system and ready for launch to facilitate rapid loading. This task would benefit from the aide of an automated process, but such a system has yet to be developed; therefore, it is assumed that UAVs are manually loaded onto the launching system by a technician.

Once the first aircraft to be launched is pre-staged on the launcher, the GCS operator, swarm commander, and flight crew chief confirm all systems are functional. The launch technician then ensures the aircraft commander is ready and initiates the launch. With one aircraft airborne, the system is manually or automatically reset to prepare for the next UAV.

Either the flight preparation or launch technician then retrieves and loads the next UAV. Systems-up status is assumed with the GCS and swarm commander after initial launch. For all subsequent launches, the launch technician only confirms with the aircraft commander for launch coordination. At any point during this evolution, any member of the crew is free to pause the launching process or cancel the mission. This procedure repeats for the remaining 48 aircraft.

For wind shifts outside of crosswind limitations, the system is reoriented. Depending on the design, this is manually executed, remotely commanded, or automatic. If automated, measures are taken to ensure the direction chosen by the system is free of obstacles and personnel.

If the launcher is located in the aircraft recovery area, it needs to be relocated prior to mission completion. Any member under the flight crew chief accomplishes this task. At the conclusion of testing, the system is deactivated and reloaded into the trailer.

Scenario Two – Multiple Launchers For the second scenario, multiple launchers are considered. This could be as few as two, but as many as 50; one for each UAV. While the scenarios begin with the unloading of the launch platform(s), it should be noted that transportation of multiple launchers is expected to increase the total system footprint. The only case where this would not hold true is if the use of multiple launchers afforded a reduction in the physical size of each unit. A potential realization of this scenario is the use of multiple bungee-type systems similar to the one currently utilized.

The same setup procedures as outlined in Scenario One are accomplished, but a trade-off occurs during this phase. It either requires more personnel to support the setup of multiple launchers, or it requires more time for a single individual to perform the task. This decision is up to the flight crew chief, but pulling manpower for launcher setup likely delays flight preparation of the UAVs. Whatever the choice, this is a more demanding task on personnel than setting up a single launcher.

The benefit afforded by this procedure is that pre-staging is simplified. Assume, for this portion of the discussion, that 50 launchers are utilized. This allows for all aircraft to be staged onto their respective launchers and standing by for takeoff. Where a technician was previously required to load each aircraft during the launch sequence, there is now a free individual standing by to aid in other requirements during the launch.

The same system confirmations occur, followed by launch initiation down the array of launch systems. For this scenario, the launch technician is solely responsible for initiating launch. The flight preparation technician loads aircraft onto the launching systems on a ready basis.

If a wind change occurs mid-launch cycle, it is increasingly complex to reorient the launchers, depending on how many are utilized. A wind shift that is 90 degrees out is cause for a complete reorientation of an abreast array, because launchers are now propelling aircraft directly into the launcher that is upwind and adjacent. Some sort of terminal area forcast (TAF) requirement may be necessary to predict future wind direction at the desired time for launch to mitigate this issue. Takedown proceeds as it did in Scenario One, but with additional manning requirements.

The requirements that originated from this section are the result of stakeholders' feedback after reviewing the scenarios. Their preference was Scenario One, that is, conduct deployments with a single launcher. At most, two launchers were considered acceptable to support the multi-launcher scenario.

Operational Requirements

1. The solution shall not include more than two, independent launcher systems.
2. The solution shall be designed such that a single operator is able to load the UAV.

2.2.4 Functional Analysis

The purpose of functional analysis is to identify the required functionality that satisfies all requirements. The chosen functions should be in direct support of the requirements discussed in this chapter. A functional decomposition diagram was used to graphically present the system in a logical, hierarchical breakout for clarity. The highest-level function is that of the system as a whole, which then expands down as various sub-functions are examined. For the purpose of this research, only the top three levels of functions were desired for analysis. This was considered to be a reasonable level of detail to adequately define a prototype development effort. The decomposition is shown in Figure 2.5.

1.0 Launch Swarming UAVs This is the highest level of functionality, and it includes all required functions of the launcher system.

1.1 Provide Launching Force This function requires the launcher to provide a means of generating the force required for UAV launches.

1.1.1 Provide Power To support the ability to provide an adequate launching force, the system must include a means of generating that energy.

1.1.2 Transfer Power With the energy provided as dictated in Function 1.1.1, the

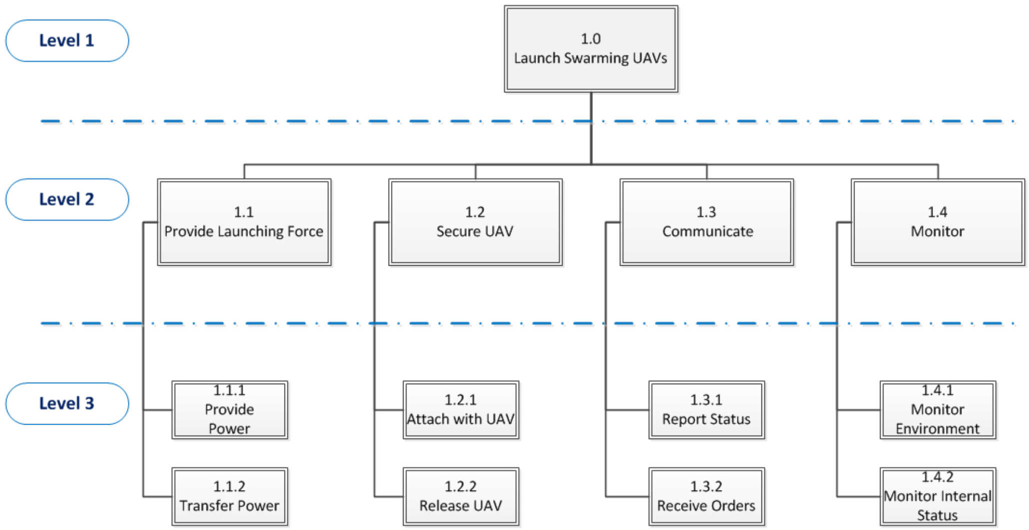

Figure 2.5: Launcher Functional Decomposition

system has to transfer said energy into usable power.

1.2 Secure UAV The system must provide a method of securement for the UAV during launch.

1.2.1 Attach with UAV At the onset of launch, the UAV must be securely attached to the launching system.

1.2.2 Release UAV At completion of the power transfer function, the system must then release the UAV for flight.

1.3 Communicate Though the degree of integration is not yet known, the system will require functionality to communicate with various external systems.

1.3.1 Report Status The system will contain the means to report current status. This may include the ready state of the launcher, the UAV's state, or perhaps maintenance status of various components.

1.3.2 Receive Orders This functionality is not limited to receiving data based orders. It also includes physical orders that the system may receive. An example of this would be the launch technician throwing a switch to command launch.

1.4 Monitor The launcher will be operated in a rapidly changing environment with various system states that must be monitored for operation.

1.4.1 Monitor Environment The launching of UAVs requires that certain environmental parameters are monitored to ensure safe launching conditions exist. The launching system will be required to provide this functionality.

1.4.2 Monitor Internal Status There should be some level of internal monitoring built into the system to facilitate the alerting of users if a degraded or unsafe state exists. Likewise, the same monitor would provide confirmation that the launcher is functioning correctly.

2.2.5 Requirement Definition

As previously stated, the purpose of this work buildup is to develop a set of requirements for the system. Some requirements originated directly from stakeholders, while others were derived to help support the identified interactions and operational concepts for the system. There are multiple approaches to selecting, classifying, and measuring system requirements. For this study, this was accomplished through the establishment of measures of effectiveness (MOE), measures of performance (MOP), functional thresholds, and system constraints.

MOEs are used to evaluate high-level, operational-related measures that evaluate key system requirements. The specific definition of a MOE can vary depending on the application. For clarity, the characteristics used in this study will be outlined. The attributes are defined in the Air Force's SMC Systems Engineering Primer and Handbook [20]:

- relates to performance
- simple to state
- complete
- states any time dependency
- states any environmental conditions
- can be measured quantitatively (if required, may be measured statistically or as a probability)
- easy to measure

MOPs, as the name implies, are performance-related measures that evaluate lower-level functionality of the system. One or more MOPs will frequently support a single, higher-level MOE. They can also be stand-alone measures to define system interface requirements or sub-system performance standards. Functional requirements are sometimes subject to objective thresholds, but for this study, they were all evaluated based on Boolean true or false measures.

Constraints are limit-based requirements that define non-performance based qualities of the system (e.g., weight, volume, dimension, cost) [21]. These may also relate to design constraints such as the stakeholder's desire for COTS components and backwards compatibility of the system.

Tables 2.1-2.3 represent the summation of all identified requirements. They are broken into high-level, performance, functional, and constraint requirement categories. As noted in Section 2.2.1, high-level requirements (R1-R9) were based on stakeholders' desires – which encompass multiple sub-categories.

The requirements relating to automation, network integration, and sensing were listed for completeness, but are not discussed as part of this report. This includes (R5), (R14), and (R15). For detailed information on the satisfaction of these requirements, refer to [22].

Table 2.1: System Requirements (High-Level)

High-Level Requirements						
Requirement Identifier	**Requirement Description**	**Measure Identifier**	**Measures**	**Measure Description**	**Units of Measure**	**Objective / Threshold**
R1	The system shall be capable of launching 50 aircraft within 15 minutes.	MOE 1	Launch Rate Performance	Measures the system's ability to satisfy the number of required launches within the given time constraint of 15 minutes.	Number of Aircraft	> 55 / 50
R2	The system shall be configured such that a maximum number of two technicians are able to setup the launcher in 15 minutes or fewer.	MOE 2	System Availability	Measures the system's ease of being available when needed for use. This will be evaluated by measuring the setup time required to bring the system online from transportation to first launch.	Setup Time (Minutes)	< 13 / 15
R3	The system shall demonstrate a failure-to-launch rate of less than or equal to 1%.	MOE 3	Launch Reliability	Measures the system's probability that it will behave predictably while in use. This will be measured by evaluating how many aircraft fail to launch out of 100 launch attempts.	Number of Aircraft	< 0.5 / 1
R4	The system shall be capable of re-orienting 90 degrees in less than or equal to 15 seconds.	MOE 4	Wind Adaptability	Measures the system's ability to adapt for variable wind conditions.	Adjustment Time (Seconds)	< 10 / 15
R5	The system shall provide a means of alerting the user to system status and potentially unsafe operations	FUN 1	Safety	Interface Function	True / False	True
R6	The system shall not require an alteration of the UAV in such a way as to make it unusable with the legacy launcher system.	CON 1	Legacy Adaptability	Interface Constraint	True / False	True
R7	The system shall utilize no more than five custom components	CON 2	Use of COTS Components	Physical Constraint	Number of Custom Components	< 5
R8	The system shall be shorter than 16 feet to accommodate transportation in ARSENL's trailer.	CON 3	System Length	Physical Constraint	Length (Feet)	< 16
R9	The prototype developmental costs shall not exceed $10,000.	CON 4	Expense	Cost Constraint	U.S. Dollar	< 10,000

Table 2.2: System Requirements (Performance and Functional)

Performance Requirements

Requirement Identifier	Requirement Description	Measure Identifier	Measures	Measure Description	Units of Measure	Objective / Threshold
R10	Following a launch, the system shall be capable of returning to a launch-ready state in less than 8 seconds	MOP 1	System Reset Time	If fewer than 50 launchers are used where system reset is required to subsequently launch another aircraft, this measures the time required for manual or automatic reset.	Time Required to Reset Launcher	< 5 / 8
R11	The UAV interface shall be capable of supporting a UAV load time of less than 10 seconds.	MOP 2	UAV Load Time	Measures the time required for the launch technician to load an aircraft onto the system. Time commences one foot from the launcher with aircraft in hand.	Time (Seconds)	< 8 / 10
R12	A maximum of two individuals shall be capable of relocating the system.	MOP 3	Portability	Measures the number of personnel required to relocate the launcher system.	Number of Personnel	< 1 / 2
R13	The system shall be capable of providing an aircraft exit velocity of 35 MPH.	MOP 4	Launch Velocity	Measures the system's ability to safely launch the Zephyr II UAV at required flying velocity.	Velocity (MPH)	> 40 / 35

Functional Requirements

Requirement Identifier	Requirement Description	Functional Identifier	Measures	Type of Function	Unit of Measure	Threshold
R14	The system shall be capable of sensing wind speed and direction.	FUN 2	Environmental Sensing	Interface	True / False	True
R15	The system shall be capable of supporting wireless data transfer with the UAV	FUN 4	System Communication Capability with UAV	Interface	True / False	True
R16	The system shall provide a method of UAV attachment for the launch cycle	FUN 5	UAV Attachment Capability	Interface	True / False	True
R17	The system shall provide a method of UAV release at the completion of the launch cycle.	FUN 6	UAV Detachment Capability	Interface	True / False	True

Table 2.3: System Requirements (Constraints)

Constraint Requirements						
Requirement Identifier	**Requirement Description**	**Measure Identifier**	**Measures**	**Measure Description**	**Units of Measure**	**Objective / Threshold**
R18	The force on the UAV's launch hook shall not exceed 20 pounds.	CON 5	System Adaptability with UAV	Interface	Force (Pounds Force)	> 20
R19	The system shall be designed such that a single operator is able to load the UAV.	CON 6	Number of Technicians Required to Load a UAV	Interface	Number of Technicians	< 2
R20	The system shall be securable, if needed, to both permeable and non-permeable surfaces.	CON 7	System Tie-Down Adaptability	Interface	True / False	True
R21	The system shall be waterproofed to so that light rain showers will not damage any component on the system.	CON 8	Environmental Survivability	Interface	True / False	True
R22	Any components of the system that are subject to degraded performance as a result of airborne particulate shall be sealed.	CON 9	Environmental Survivability	Interface	True / False	True
R23	The system shall be capable of transportation through a standard-width doorway of 36 inches without disassembly.	CON 10	Maximum Width For All Orientations	Physical	Width (Inches)	< 35
R24	The system, if not mounted on a mobile platform, shall not exceed 80 pounds.	CON 11	System Weight	Physical	Weight (Pounds Mass)	< 80
R25	The system, if mounted on a wheeled platform, shall not exceed 160 pounds.	CON 12	System Weight	Physical	Weight (Pounds Mass)	< 160
R26	The system, if mounted on a motorized wheeled platform, shall not exceed 500 pounds.	CON 13	System Weight	Physical	Weight (Pounds Mass)	< 500
R27	The system shall not include more than two, independent launcher systems.	CON 14	Number of Launchers Required to Accomplish Launching Mission	Design	Number of Launchers	< 2

CHAPTER 3:
Market Evaluation

The final task of the decomposition phase is to research potential solutions and determine if a ground-up design effort is warranted. For ease of reference, the systems engineering (SE) diagram is presented again in Figure 3.1.

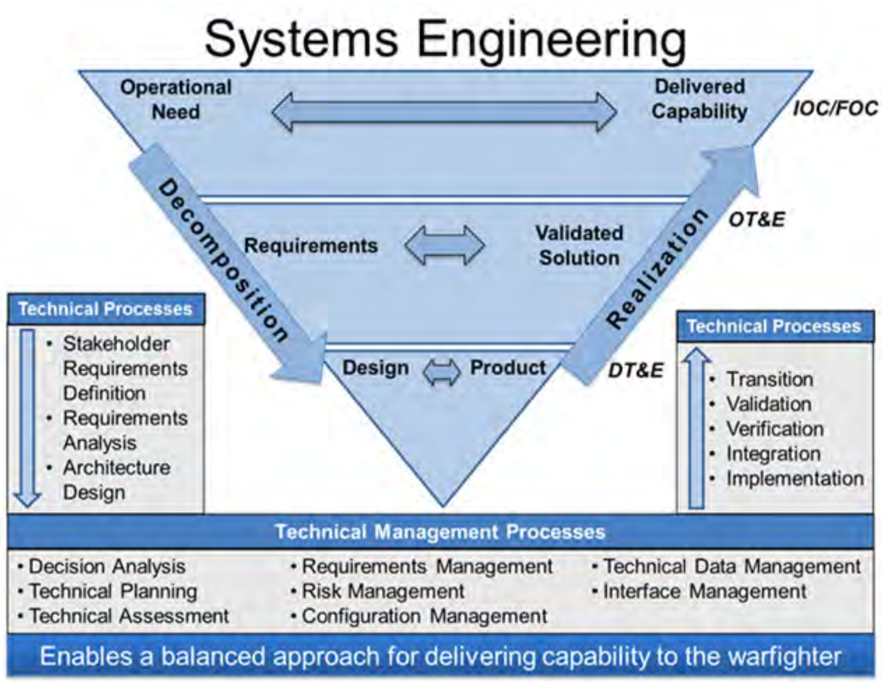

Figure 3.1: DOD SE Process Overview, from [19]

Activities that were performed during this phase included market research and an analysis of alternatives (AoA). These efforts are intended to aid in the identification of the following pieces of information:

Market Research

- It is possible that previously undiscovered products currently exist that are capable of satisfying, or coming close to satisfying, the system requirements. If this is the case, the design process is greatly simplified or eliminated altogether.

- Understanding similar systems promotes the identification of desirable and undesirable system traits based on design requirements.
- Market research helps to build a broad understanding of the engineering techniques that may be required during a design process.

Analysis of Alternatives

- If multiple solutions are found to exist, the AoA process develops a set of standards to determine the optimal solution.
- Alternatively, this process, combined with system requirements, builds the standards required to determine if commercial solutions are not viable. If this determination is made, a baseline design effort is warranted.

3.1 Market Research

The original intent of this research was to conduct a full, world-wide survey of existing unmanned aerial vehicle (UAV) launchers. Various entities in both industry and DOD sectors publish similar documents on the UAVs themselves; however, no such document is believed to exist for launchers. During the research effort to accomplish this, language barriers and a general lack of documentation required a reduction of scope. To remedy this, the study is limited to include only well-documented launchers utilized or developed by U.S. industry, academic institutions, or the DOD. Also, this market study is not intended to be an all-inclusive list of available solutions. Rather, the desire is to conduct a search broad enough to build the aforementioned knowledge base of existing UAV launcher technologies.

A few conclusions are immediately apparent as result of the study. There is a general lack of information available for UAV launching systems. This is primarily attributed to a low degree of innovation in the designs. As a result of this, there is not a high degree of competition in the market. It appears the general stance is that, if the aircraft platform is safely launched, the launcher is acceptable and does not warrant further discussion. The primary selling point for commercial UAV manufacturers is the UAV itself; the launcher is bundled as a ground support item. The limited cases for which comprehensive information is available are for the few companies producing launchers compatible with multiple UAV platforms. Their marketing strategies lead to the second conclusion: the market is not yet responding to swarming UAV scenarios. Frequently highlighted features of an advertised system are its ease of setup and portability. This is likely because these two variables greatly affect the versatility and ease-of-use of the UAV. However, parameters critical to swarming scenarios, like UAV loading and system reset times, are rarely mentioned.

The first phase of the research effort is accomplished by identifying UAV platforms that were, and are currently, in use by the U.S. Search engine results were compiled into a spreadsheet where each UAV was then individually studied to determine its method of launch. A total of 156 UAV platforms were examined. Of those platforms, 43 utilize some form of identified launching method. The remaining UAVs are either out of service, so poorly documented that the launching method could not be determined, utilized a runway for takeoff, or were vertical take-off and landing (VTOL) systems.

The research was then re-directed to specifically target launcher systems. In some cases, launchers are not aircraft-specific; ergo this aided in identifying cross-platform systems. Nine additional UAV launchers were identified. Some of these systems are developed in other countries but available for purchase through U.S. distributors; therefore, they were included.

Finally, active UAV research laboratories linked to various academic institutions were explored. Results from 24 identified universities with UAV programs revealed that only two are engaged in a targeted study of UAV launcher technologies. The other facilities that utilized a UAV launcher as part of their research have acquired commercial systems.

Prior to discussing specific results, the limitations of the survey should be understood. Due to the previously noted lack of data available, many systems are categorized based only on physical appearance or video-recorded launch sequences. In the case of hydraulic systems, the appearance and operation is very similar to that of pneumatic. For this reason, all systems using a piston setup were classified as pneumatic. Also, the method of research does not accurately reflect the abundance of bungee-type launching systems. When targeting launchers used for specific UAV airframes, bungee systems are only counted once. However, their simplicity and ease of adaptability to light and medium-weight UAVs allows them to be utilized for multiple platforms. Additionally, because bungee systems are generally inexpensive and can easily be constructed with minimal hand tools, they are frequently used without any formal documentation. Finally, the historic abundance of rocket-assisted take-off (RATO) type systems returned too many results to be fairly compared against more modern bungee and pneumatic solutions. To remedy this, only current or recently (within 10 years) active pyrotechnic launchers are considered.

For a summary of results, the above constraints are implemented, and the percentages of each type of system represent the fraction with respect to those actually using a launching system. Hand-launched UAVs are removed from the study. Results show that more than half of the explored market employed some variation of a pneumatic system. Bungee systems are the second most-frequently used launch system at approximately 18 percent, but this is not believed to be an accurate reflection of their widespread use. Pyrotechnic systems are the third most prevalent, followed by the two testing platforms designed for carrier use. These values are shown in Table 3.1.

Table 3.1: Summary of Market Results

Parameter	Data
Number of Entities Researched	188
Number Using Launching Systems / Not Hand-Launched	27
Percent Using Pneumatic	62.96%
Percent Using Bungee	18.52%
Percent Using Pyrotechnic	11.11%
Percent Using Aircraft Carrier	7.41%

Using the parameter breakdown shown in Table 3.1, various design features are discussed in the following sections. The high degree of commonality allows for an abbreviated overview; therefore, rather than address each launcher individually, sample systems are selected from each parameter class, with the exception of the aircraft carrier catapult, to represent the frequently observed engineering features.

Pneumatic

The Arcturus Portable launching system, when assembled, is a 175-pound aluminum and composite pneumatic launcher [23]. The system features a nitrogen or compressed air accumulator attached directly to the launching tube. When launch is desired, a pull chord is activated that allows the pressurized gas to transfer into the launch tube. A launch rod resides inside the launch tube and is attached to the UAV. The rod is accelerated by the expanding gas and ejected from the system. Shortly after ejection, the rod falls and separates from the UAV and lands a few feet from the assembly. There is no mention of an included compressor, hence it is assumed that multiple accumulator bottles or separate compressor systems would be used for multiple launch scenarios. This system is shown in Figure 3.2.

Figure 3.2: Arcturus Portable Launching System, from [23]

The UAV Factory Pneumatic launcher is available in both 6 and 12 kJ power options [24]. These launchers are also highly portable and can be broken down into a hardened suitcase for transportation. They are remotely activated for launch where high-pressure air is vented into the departure end of the launch rail. A pulley at the departure end transfers the energy from an internal plunger to the UAV cradle via cables. At completion of the launch stroke, the UAV cradle is arrested and pressure is vented. The included compressor refills tanks in approximately 10 and 20 minutes for the 6 and 12 kJ versions respectively [24]. This system is shown in Figure 3.3

With the exception of a few novel approaches, these two examples are fair representations of the common setups observed for lightweight pneumatic launchers. For heavier pneumatic systems (up to several tons in weight), the structure is significantly more complex, but the implementation and mechanical configuration of the launching section are of similar design.

Figure 3.3: UAV Factory Pneumatic Launchers (6 and 12 kg), from [24]

Bungee Systems

Two basic types of bungee systems were found. The first was identical to the design currently used by Advanced Robotic Systems Engineering Laboratory (ARSENL). It consisted of a set of PVC or aluminum launch rails with a bungee anchored at some distance from the rails. The only variation on this design was that some included a foot-pedal operated bungee holdback fitting to avoid having to manually hold the aircraft in place under tension. For brevity, this type of system will not be re-presented.

The second type functioned similarly to the light-weight pneumatic systems using a series of pulleys to propel the UAV but retain the cradle. An example of this is produced by Air-Vision-Air. The catapult is capable of delivering enough force to launch a 13-pound aircraft at 25 mph [25]. The cradle is retained post launch, and the user then redirects the bungees over the pulleys and manually retracts the cradle to re-apply tension. This system is shown in Figure 3.4.

Figure 3.4: AVA Bungee Launcher, from [25]

Pyrotechnic Systems

There were only two current or recently active pyrotechnic systems found. The first one to be discussed is the launching system of the RQ-5 Hunter. The RQ-5 was co-developed by Israel Aerospace Industries (IAI) and TRW (now Northrup Grumman), and was used by the United States Army starting in 1996 [26]. More modern iterations of this platform have since been developed, and it is unclear if they still employ RATO launching capabilities. Though limited data were available for the original launcher, it appears to be a simplistic system consisting only of a launch platform to direct the UAV during rocket ignition. This system is shown in Figure 3.5.

Figure 3.5: RQ-5 Hunter RATO Launch, from [26]

The second pyrotechnic system found was the launcher for the AeroVironment Switchblade UAV. The switchblade is still under development at the time of writing, but it represents a noteworthy advancement in launcher mobility and compactness. Though the details of functional operation are not known, the launcher appears to operate in a fashion similar to mortars. The UAV's wings fold to fit inside the tube and expand upon exit. The system is shown in Figure 3.6.

Figure 3.6: Switchblade Tube Launch, from [27]

3.2 Analysis of Alternatives

To conduct an AoA, a launcher classification system was developed to aid in the targeting of systems with desirable characteristics. For example, an aircraft carrier's catapult system is deemed out-of-scope because it significantly exceeds the aircraft weight requirements necessary for a six-pound UAV. The classification system shown in Table 3.2 was conceived over the course of research from observed characteristics of existing launching systems and probable future configurations.

Table 3.2: UAV Launcher Classification

Category	Characteristic	Selected Within Scope
Power Generation	Bungee/Spring	X
	Pneumatic	X
	Hydraulic	
	Electromechanical	X
	Electromagnetic	
	Pyrotechnic	
	Self/Gravity	X
Power Transfer	Direct/Guided	X
	Pulley	X
	Lever Arm	X
	Projectile	
UAV Weight Range (Pounds)	Small Group 1 (< 20)	X
	Medium Group 2 (21 - 55)	X
	Large Group 3 (< 1320)	
	Larger Group 4 (>1320)	
	Largest Group 5 (>1320)	
Mobility	Human Carried	X
	Human Portable	X
	Self-contained	X
	Vehicle Towed/Mounted	
	Stationary	

The column on the left denotes the category; the center column shows the various characteristics that define a launching system within each category; and the column on the right indicates whether or not the launcher was considered to be within scope for the AoA. If alternative solutions are well outside of system requirements, they are eliminated from further analysis. An "X" indicates the characteristic is considered within scope and included for study.

The power generation category is used to differentiate launching systems based on how they store potential energy. The power transfer category shows the frequently found methods for energy transfer or amplification of the launching force or velocity. The aircraft weight-range for which the launching system was designed is considered the best method for determining power available. Depending on the type of power generation utilized, it was found that power was frequently documented using metrics that were difficult to compare. For example, pneumatic systems may list the pressure ratings for the cylinder while electromechanical systems list motor power in watts or horsepower. Also, depending on how the energy is transferred, the power actually transferred to the aircraft can vary greatly. To use a consistent unit of measure, the DOD-defined weight categories for a UAV's maximum gross takeoff weight is used [28]. To avoid confusion, it should be mentioned that the determining difference for a Group 4 and Group 5 UAV is maximum cruising altitude, not weight. The last category addresses the mobility of the launching system.

A detailed description and justification for in-scope selection is provided in the following sections, but first, a visual depiction of the terminology used aids in the description discussion. It contains the major components common to many launchers. The actual design and integration of these components varies greatly, but the core functionality remains the same. Figure 3.7 is a computer-aided design (CAD) image generated using SOLIDWORKS software of a sample UAV launching section. From this point forward, all referenced CAD images were created using SOLIDWORKS software. Also, some components of the assemblies shown in the CAD are sourced from the McMaster-Carr database [29].

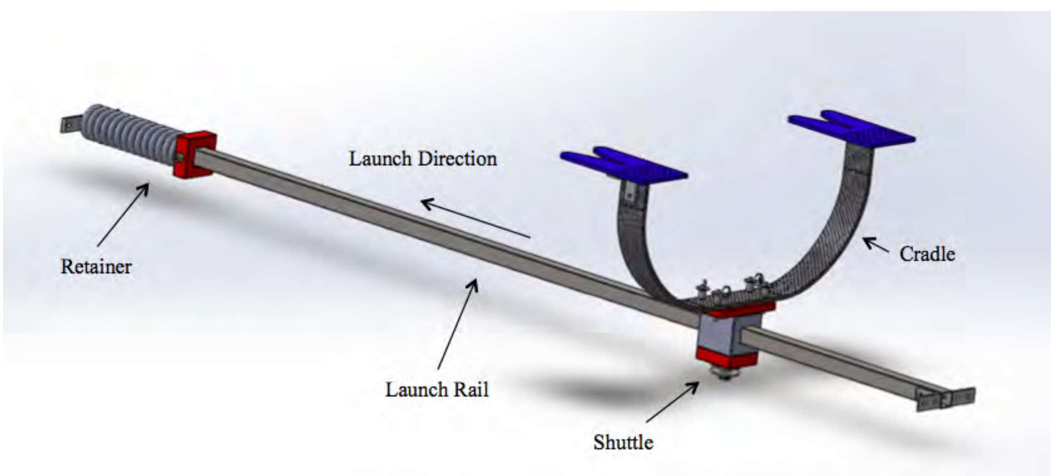

Figure 3.7: Common Launcher Components

The component names were created according to the preferences of this author, but they share terminology and were inspired by aircraft carrier catapult systems. The "launch rail" is the portion of the launcher that directs the aircraft during launch. The "shuttle" is the component guided by the launch rail that interfaces with the cradle. The "cradle" physically holds the UAV in place. In some cases, the shuttle and the cradle are the same component. Finally, the "retainer" is the device responsible for stopping the shuttle at the end of the launch stroke. With an understanding of the basic terminology used for this section, Table 3.2 will be explained.

1. Type of Power Generation

   Bungee/Spring Bungee or spring systems store the required energy for launch by physical compression or extension of the elastic component. They are typically inexpensive, lightweight, and relatively simple to implement. Using ARSENL's existing launcher as an example of the simplicity, this system does not require a shuttle or retainer. For these reasons, bungee and spring systems are included for the study.

   Pneumatic Pneumatic systems are found to be the most common. They utilize compressed air to generate the necessary launching force. Due to the prevalence of these types of systems, they are included for study.

   Hydraulic Hydraulic launchers are less common than pneumatic, and they have higher pressure requirements for the hydraulic fluid than their pneumatic counterparts. The ARSENL team wants to avoid the required safety actions for high-pressure systems, as well as the inherent complexity to generate the required pressure; therefore, these systems are not included for study.

   Electromechanical Electromechanical systems use rotary or linear electric actuators for launching power. These can be the sole source of energy, or they can be used in combination with bungees or springs. These systems are well suited for field use where batteries can serve as the primary power source without the need for a generator; hence they are included for study.

   Electromagnetic Electromagnetic systems are essentially modified rail guns using fluctuating magnetic fields to propel a ferrous shuttle down the launch rail. These systems are highly complex and demand a significant amount of electrical power. For these reasons, they are not included in the study.

   Pyrotechnic Pyrotechnic systems utilize a combustive compound to set off a controlled explosion for propulsion. This is similar to a tube-and-mortar type of weapon. Also, RATO used in combination with a launch rail are placed in this category. The safety concerns and transportation issues with handling these compounds are extensive and undesirable for this design. For this reason, they are not included in the study.

Self/Gravity Self-propelled systems use the UAV's own power to propel the aircraft. Likewise, gravity systems allow the aircraft to "slide" down a ramp to generate velocity. Both of these concepts may be realized with a relatively simple solution because the launcher does not inherently store energy. For this reason, they are included for study.

2. Type of Power Transfer

Direct/Guided A direct or guided system does not use mechanical advantage to propel the UAV. ARSENL's existing bungee launcher is an example of a direct-launch system. Other examples of this type of system are self or gravity launchers. This type of power transfer reduces mechanical complexity, which offers advantages worth exploring; therefore, it is included in the study.

Pulley Power transfer and amplification via pulleys is the most common type of setup found. In these systems, one or more pulleys are utilized to create mechanical advantage for the system. Pulley systems, in contrast with lever arms, allow for inline orientation with the launch rail, which contributes to a reduced footprint. The abundance of existing systems and the general compactness of this power transfer method make it worth including within the scope of this study.

Lever Arm Lever arms accomplish the same end-goal as pulley systems. They are simply another means of amplifying velocity or power. Tradeoffs between the two methods will be discussed further, but for the purpose of market research, this type of system is included as a potential approach.

Projectile These systems transfer power using a projectile that detaches from the launch rail. The advantage of projectile-type systems is that, because the sled detaches, there is no need to stop it at the end of the launch stroke, thus eliminating the retainer and associated impact. However, due to the safety concerns inherent with uncontrolled objects departing the launcher, this method is eliminated from study.

3. Aircraft Weight Range

   Small Group 1 (< 20 Pounds) This category of UAV is the most applicable to the design effort because the Zephyr II falls under Group 1; therefore, it is included for study.

   Medium Group 2 (21 - 55 Pounds) Although Group 2 aircraft are larger than ARSENL's, they are still close enough in weight that the launching systems warrants inclusion.

   Group 3 - 5 Launcher systems designed for aircraft heavier than 55 pounds are not included because the complexity required is not warranted for a six-pound UAV.

4. Mobility

   Human-Carried Human-carried systems are launchers light enough and compact enough to be lifted and transported by a single individual. This meets the stakeholder requirements for mobility; therefore, they are included.

   Human-Portable Human-portable systems are launchers that are either light enough, or incorporate appropriate mechanical advantage, for one or two humans to relocate. These systems also meet the stakeholder requirement; therefore, they are included.

   Self-Contained Self-contained mobility is characterized by a launching system that has built-in power for relocation. It became ambiguous to differentiate between self-contained and vehicle-mounted launchers. To mitigate the issue, a total system weight threshold of 500 pounds is arbitrarily established for self-contained systems. The on-board power source for mobility allows for a single individual to relocate these launchers; therefore, they are included for study.

   Vehicle Towed/Mounted These systems are either towed by a vehicle, or designed to be mounted to a vehicle. A "vehicle" includes ships, land units, and other aircraft. They are not included for study because these systems exceed the requirements to be transported inside ARSENL's trailer.

   Stationary Stationary units are permanently mounted on location. There are not any examples of this type of launcher found, but there is potential for them to be implemented at some point in the future. An example of this may be a system similar to an air defense missile silo where UAVs are launched as the defensive countermeasure. This type of launcher utilization was outside of the stakeholders' requirements, and there are not current examples. For these reasons, it is not considered for further study.

Using these metrics to narrow the acceptable results found in the market survey, only three systems remain. They are the Lockheed Martin Stalker, the UAV Factory Pneumatic Catapult, and the AVA Bungee Launcher. The Lockheed Martin Stalker is removed because it is an identical system to ARSENL's bungee launcher. The specifications for the remaining two systems are shown in Table 3.3. Refer back to Figure 3.3 and Figure 3.4 for images of these launching systems.

Table 3.3: Launcher Specifications, after [24], [25]

Specification	**UAV Factory**	**AVA**
Power Generation	Pneumatic	Bungee
Power Transfer	Pulley	Pulley
UAV Weight Range	Group 1 and 2	Group 1
Mobility	Human Portable	Human Carried
Rail Length	13.1 feet	11.2 feet
Maximum Launch Velocity	53.7 mph	25 mph
Launch Pressure	145 PSI	N/A
Reset Time	< 10 Minutes	< 2 Minutes
Weight	242.5 Pounds	58 Pounds

Of the two options commercially available, neither is capable of meeting the established requirements. The reset time of the UAV Factory pneumatic launcher would require that 40 units be deployed to meet launch-cycle time requirements. Also, utilizing this many of their launchers would weigh approximately 10,000 pounds. This far exceeds the trailer's weight and space limitations. AVA's bungee launcher would require four launchers to meet this same requirement. From a size and weight perspective, this is feasible as the units are compact and lightweight; however, the launcher is not designed for automated reset. To take advantage of the four-launcher system, one would need four launch crews – one to operate and reset each system. ARSENL does not have the manpower to support this many launch crews. Also, the AVA falls below the required launch velocity of 35 mph for Zephyr II UAVs. Increasing the bungee strength for greater end velocity would likely require a re-design of all tensioned components and was not thought to be practical. Having ruled out the purchase of a commercial system, the research necessarily pivots towards design and development of a custom integrated launching system.

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CHAPTER 4: Design Development

Concept generation is the first step in the physical design development process. Also, it marks the beginning of a transition period from decomposition to realization in the systems engineering (SE) V model.

4.1 Concept Development

Developing concepts is an important phase in the design process. The baseline solution for an eventual prototype is created during this effort; therefore, it is critical the process be fully inclusive. All possibilities should be examined with equal consideration. The purpose of the process is to exhaustively explore potential solutions and then select the best candidate for further development. For this thesis, concepts are eliminated or selected based primarily on the following two criteria:

Satisfaction of Requirements The concept needs to satisfy the stakeholder requirements as identified in Chapter 2. This was not an easy determination to make because the concepts were only basic drawings of potential solutions. Without analytical data, decisions were based on the combined experience of the Advanced Robotic Systems Engineering Laboratory (ARSENL) team, stakeholder feedback, and the author's extensive background in lightweight, remotely-piloted aircraft.

Design Simplicity This is a key limitation and factor to consider during concept generation. Simplicity was also important to the stakeholder as a predictor for future reliability. In general, lowering the complexity of a system tends to have a positive impact on the reliability. Also, the solution had to be developed within the manufacturing and technical limitations of just two individuals. In addition to this thesis, a parallel effort to design and build the required automation and sensing capabilities necessary for the mechanical solution to function is presented in [22].

4.1.1 Previous Work

The concept generation phase was influenced by previous work completed as part of a Naval Postgraduate School (NPS) capstone design team. This was a seven-person group working to achieve the same launching capability for the ARSENL. The lessons learned are directly applicable to the concept development phase and should be discussed.

The design featured a pneumatic actuator connected to a lever arm for mechanical advantage. The prototype was named "RULE" for Rapid UAV Launch Engine. The computer-aided design (CAD) image is shown in Figure 4.1.

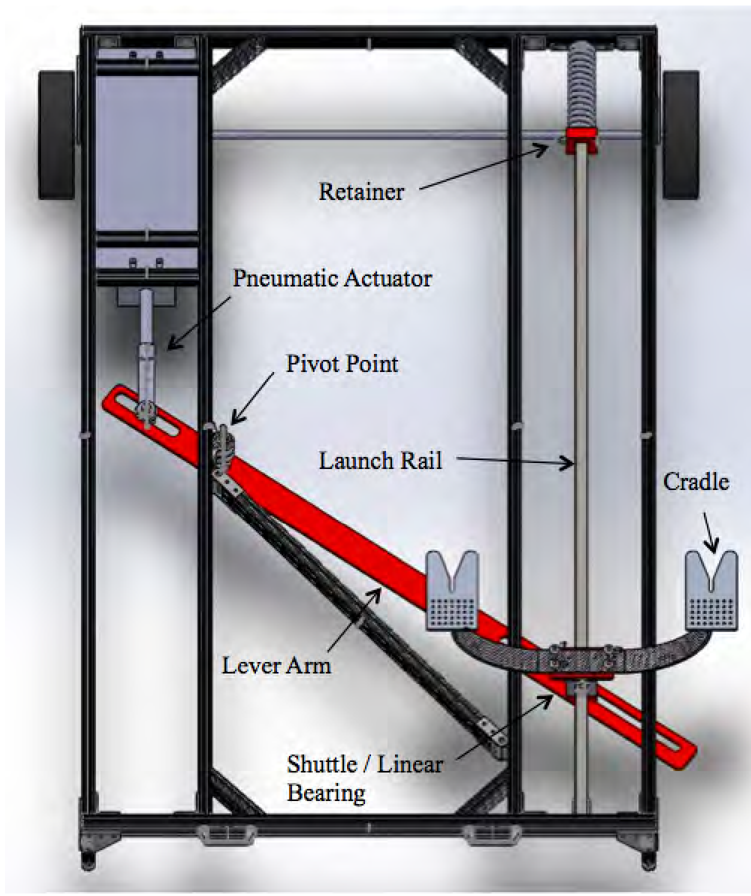

Figure 4.1: Schematic of the Rapid UAV Launch Engine Prototype

An external air compressor provided pressure for the system, and an electronically controlled solenoid was used to remotely trigger launch. The velocity of the pneumatic rod was amplified 4:1 using a lever arm for mechanical advantage. This energy was transferred to a linear bearing with the unmanned aerial vehicle (UAV) cradle attached. At completion of the launch stroke, position sensors shut off the pressure, and the retaining spring stopped the shuttle assembly. The UAV departed the cradle as a result of the rapid deceleration. Reset was accomplished by providing low-pressure air to the opposite side of the pneumatic. A picture of the completed prototype is shown in Figure 4.2.

Figure 4.2: Photograph of the RULE Prototype during Outdoor Experiments

4.1.2 Lessons Learned

The RULE prototype was unable to provide the necessary velocity for launch. However, it was a valuable learning experience that provided a significant amount of insight for future design considerations.

Engineering Considerations

1. The use of CAD proved highly beneficial. The CAD model allowed for rapid design changes without the need to physically assemble hardware. At the time of building, the system was assembled without the need for hardware modifications.
2. While extruded aluminum was not the lightest framing option available, it allowed for ease of construction and ease of modification for design changes. It also provided a simplistic approach to mounting various hardware components, because no drilling was necessary.

3. The use of precision components requires all interfacing parts to be of equal precision. The linear bearing was designed for a precision ground shaft. Ground shafts were not available at the desired length; therefore, a welded stainless launch rail was used instead. In order for the linear bearing to freely slide down the launch rail, its positioning plates had to be loosened extensively. This resulted in a significant amount of play between the bearing and the rail and undesirable rocking in the UAV cradle assembly.
4. The attempt to maximize the use of commercial, off-the-shelf (COTS) products meant many components were being implemented in unconventional applications. For example, a car door lock was repurposed as the safety holdback for the swing arm. This type of component adaptation was expected for a design like this, and in some cases, it was perfectly acceptable. However, there were several points in the design that were absorbing forces either in magnitude or direction that exceeded component recommendations. The consequence of this was the necessity to add bracing at several points in the structure. Testing showed that bracing one point usually led to failure elsewhere or more bracing, which leads to an infinite loop. The net takeaway for future prototypes was to ensure COTS components that were under load were being stressed in accordance with their specifications.
5. All losses in a system must be accounted for when using mathematical modeling to size components. When characterizing the physical interactions of a complex system, assumptions are usually made to account for losses. While the team tried to error on the side of caution, the omission of key considerations resulted in failure to reach required launch velocities. The focus, at the time of design conception, was on losses associated with frictional forces in the swing arm assembly. This was properly mitigated; however, testing revealed airflow restrictions from the compressor that were not calculated. This resulted in low flow rates that were unable to fully power the launch stroke.
6. The location and method of UAV engagement with the cradle was critical. Intuitively, this was known to be an important interface, but the extent to which the supporting structure could adversely affect the launch was underestimated. For this particular setup, the cradle had a “V” cut in the leading edge that would en-

gage with two nylon bolts anchored in the UAV's wing. The bolts were located on the aerodynamic center. This is approximately two inches aft of the center of gravity. When the launch stroke was complete, the intent was for the nylon bolts to slide out of the "V" with minimal effort and low pitching moments. However, testing revealed that the friction between the bolt and the cradle was high enough that it caused a nose-down pitching moment. This resulted in the UAV immediately being redirected into the ground.

7. While pneumatic systems were the most prevalent in studies, these solutions were not intended to rapidly reset for follow-on launches. A rapid reset required additional support equipment. The swarming scenario did not allow for pre-charged tanks. A tank large enough to support 50 launches was not practical. Therefore, a compressor was required. In total, the system required both 12- and 24-volt DC power supplies for the sensor suite, a 120-volt AC supply to power the compressor, and a compressor. All of this took time to set up and required power outlets for operation. The testing facilities for ARSENL were able to support this, but it was a cumbersome process and limited the launcher's mobility.
8. High-speed video analysis showed the propeller, though unpowered, windmilled during launch. This was previously an unknown occurrence to ARSENL and mandated that the propeller be secured for launch, or the full arc be free from obstruction.
9. Energy absorption of the launch shuttle was a significant source of stress on the system. High-speed video showed both torsional and longitudinal flexing of the framing structure when the shuttle was arrested. Although a structural failure did not occur during testing, it was reasonable to conclude that repeated launches would eventually weaken the structure or loosen fasteners. Fixing this issue became a top priority for future prototypes.

Operational Considerations

1. The RULE launcher was able to support the cycle time requirement of one launch every 18 seconds. The design focus and enabler to accomplishing this target was the automated reset function of the launcher. However, other factors of importance noticed during testing were actual loading times of the UAVs

and crew coordination. The system was mechanically capable of being reset in under five seconds, but most of the time between launches was due to staging times for the UAV and communications between the various operators. Streamlining this process through automation or smart design should be incorporated into future prototypes for enhanced performance.

2. The RULE launcher required the ARSENL team to manually load and run software from external computers to manage the sensor suite and launching functions. From their perspective, this was undesirable and should be redesigned internally to the system with a simple On/Off switch.
3. The large footprint of the launcher took up valuable floor space in the trailer. Launch velocities achievable were directly proportional to the length of the lever arm. In other words, to achieve higher velocities, the assembly would need to be widened. This became a logistics issue with transportation.

4.1.3 Concepts

In addition to meeting system requirements within the engineering limits of the design team, the top priority going into the concept development phase was to design a system free from impact. The only method seen in the market study for achieving this capability was to utilize a projectile-type launcher where the shuttle assembly departs the system after the launch stroke. However, this method was eliminated as an alternative as discussed in Section 3.2. Therefore, new approaches needed to be developed.

The first approach explored involved using extended throw dampeners to increase the impulse of stopping the shuttle. In the RULE design, a spring dampener was used for this purpose. However, COTS springs with the required spring coefficient to arrest the shuttle only compress a few inches. This was too rapid of a deceleration to mitigate the effects of an impact. In an effort to promote simplicity, the concept shown in Figure 4.3 used the same bungee system as both the launching force and dampener. This eliminated the need for additional dampeners.

The concept utilizes a locking pivot to allow the bungee support beams to collapse for transport. The launch rail is mounted above the bungee supports as a floating sub-assembly to allow the shuttle to traverse the full 20-foot length of the launch rail. Length was arbi-

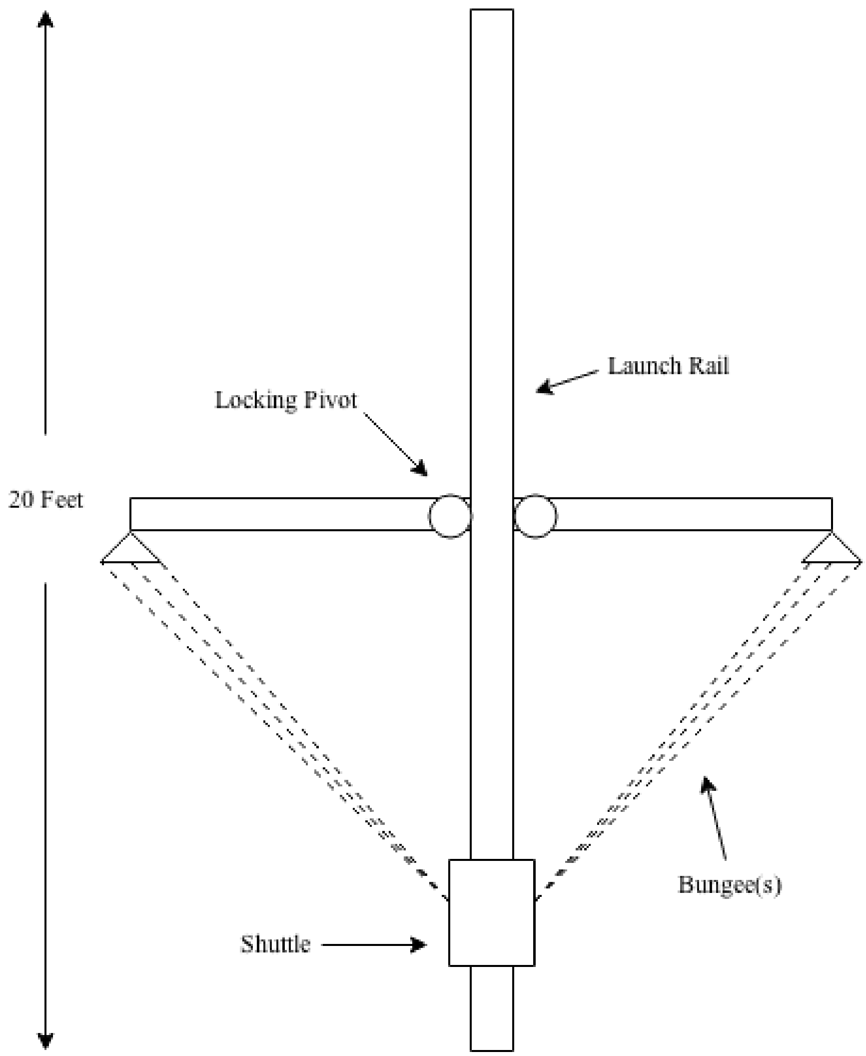

Figure 4.3: Top View of Bungee Concept

trarily determined as a starting point based on common launcher lengths observed during the market analysis.

Envisioned operation would use an electric winch to retract the shuttle to the launch position and tension the bungees. The aircraft would then be mounted onto a cradle assembly and launch would be achieved by releasing the winch holdback. Maximum velocity would occur at the mid-stroke point (10 feet down the rail) where some type of UAV release mechanism would be required to detach the UAV. As the shuttle slides past the mid-point, the bungee assembly progressively rebuilds tension, arresting the motion. Major drawbacks to this concept and the reasoning for cancelling further development were:

1. Assuming the coefficient of friction between the shuttle and the launch rail is low, this system would oscillate for some time following the launch before coming to rest. Dampening the oscillations at an accelerated rate requires the addition of electrically-controlled brakes, adding to the complexity.
2. While the concept effectively eliminates impact, doing so with this method requires the launch rail to be twice the length desired for actual launch. This negatively impacts transportation or, if the rail were broken into two sections, it would significantly complicate the structure.
3. From the perspective of the launch technician, the shuttle assembly is returning directly at the operator at a velocity near that of launch. Assuming safety concerns are mitigated, it was determined this would likely be unsettling for the user.
4. Finally, ARSENL stakeholders were not in favor of aircraft release being dependent on timing mechanisms. It was assumed the release would be software-based. Any lag in processing performance or missed cues results in a failure to launch. Additionally, failed launch on this system meant the UAV is now riding on a violent pendulum until the oscillations subdue.

The second concept considered was an adaptation of a typical pneumatic system. The reason the capstone design team originally decided to use a swing arm in favor of pulleys was the ease with which it automatically reset. All researched commercial systems using pulleys for mechanical advantage required manual reset once the pulley cables were slack following a launch. In some cases, the cables actually required re-routing back onto the pulley assembly as the slack allowed them to fall out. To mitigate these issues, the concept shown in Figure 4.4 was conceived.

The concept shown utilizes two pneumatics for control of the cable tension during launch and reset. Mechanical advantage is achieved by stacking an array of pulleys such that one unit-of-length change in the pneumatic results in four units of motion at the shuttle assembly. Adding or removing pulleys in the pulley assembly alters this ratio.

Envisioned operation would use electrically-controlled solenoids to simultaneously retract

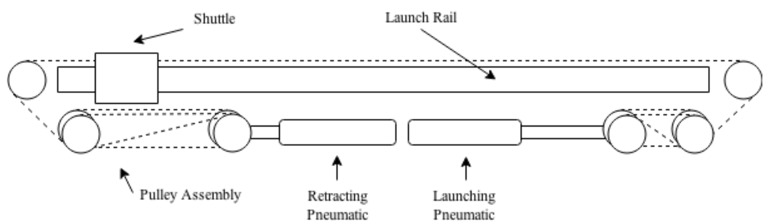

Figure 4.4: Side View of Pneumatic Concept

the launching pneumatic while extending the retracting pneumatic. The harmonization of the pneumatics would control cable tension throughout the launch stroke. Also, the addition of a retracting pneumatic allowed for automatic reset of the shuttle assembly. Logic could be incorporated for the retracting pneumatic to function as the dampener at the end of the launch stroke to arrest the shuttle prior to impact. Major drawbacks to this concept and the reasoning for cancelling further development were:

1. Although this concept solves the large footprint issues associated with the RULE design, it does not eliminate the burdensome support equipment required for pneumatic systems.
2. Core functionality of the system requires the pneumatics to be perfectly synchronized. This was thought to be a highly complicated endeavor that would involve significant programming and perfectly mirrored air sources. Given the limited timeframe available for development, it was not thought to be a viable option.

These two concepts were an attempt to adapt the principles found during market research and the capstone effort to meet system requirements. There were other variations not presented, but they were similar in concept with only minor adjustments. At this point in the concept development, it was decided to depart from known methods and approach the problem from a new perspective. Rather than focus on UAV launching technology, the scope was broadened to include any system that rapidly accelerated an object from rest.

The augmented focus allowed for exploration of new systems like spring-loaded throwers used for clay pigeons and roller coaster acceleration methods. For the most part, the complexity or mechanical setup of these systems did not lend themselves well to UAV launchers. One, however, stood out as viable.

Baseball pitching machines operate on the principles of inertia and friction. One or two flywheels are accelerated to desired velocity, and a relatively lightweight baseball is inserted into the mechanism. The baseball is then compressed against the flywheel and ejected at a velocity approximately equal to the tangential velocity of the flywheel. Due to the inertial mismatch of the flywheel and the ball, the system is only marginally decelerated during the process. Also, a relatively low-powered motor drives pitching machines. A follow-on pitch is immediately achievable as the flywheel is continuously spinning, and there is not an impact as a result of the launch. Going forward with this concept, several iterations were developed that eventually led to the chosen design approach.

This marked an important transition from concepts using observed power-generation characteristics like bungee and pneumatic to an electromechanical system. Recall from Chapter III that market analysis did not reveal any existing systems that use an electric motor as the power generation method. There were risks associated with developing an untested method, but the uniqueness of the swarming scenario mandated a departure from established practices. These risks will be discussed in greater detail in Chapter 5.

The first concept was essentially a lengthened pitching machine redesigned for UAVs. The concept features two drive pulleys, each powered by an electric motor. Along the length of the assembly, spring-tensioned idler pulleys maintain proper grip on the UAV for the launch. This concept is shown in Figure 4.5. Note that the graphical depiction is for representation only and is not to scale.

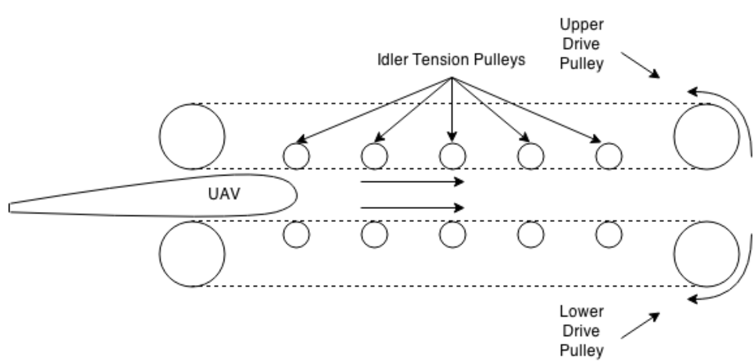

Figure 4.5: Side View of Pitching Machine Concept

Envisioned operation would be similar to that of a baseball-pitching machine. Power would be applied to the drive motors, thereby accelerating the conveyor belts to desired velocity.

At this point, the UAV would be inserted into the system, accelerated, and ejected from the far end. The compression of the belts would provide adequate holding power for the UAV without the need for a cradle assembly.

While the stakeholders approved of the general concept, there was concern expressed that Zephyr II UAVs may not withstand the instant acceleration force generated by the system. The Zephyr II wing is constructed from foam with a shrink-wrap type of film covering for protection. The grip between the conveyor belts and the film would likely rip the covering upon insertion of the UAV. To mitigate this, a progressive velocity concept of the same principle was created. This system is shown in Figure 4.6.

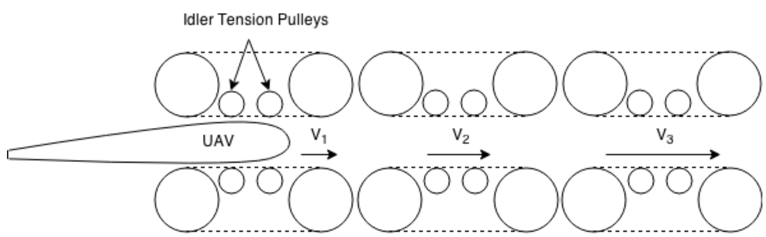

Figure 4.6: Side View of Progressive Pitching Machine Concept

Envisioned operation for this system is similar to the original pitching machine concept. The difference between the two is that the conveyor is set up in multiple stages for progressively higher velocities. This would mitigate the initial shock as the UAV accelerates in stages through the launching section.

Although the concept was generally favored as a viable possibility for meeting design requirements, the stakeholders did not approve of the necessity for six independent drive motors. At best, the upper and lower drive pulleys of each section could be linked to one motor, but that still required three motors. The complexity and power requirements for this concept required further refinement.

In an effort to simplify the staged pitching-machine concept, consideration was given to removing the upper conveyor assemblies and replacing them with a fixed hold-down. This is shown in Figure 4.7.

Operational concept is the same for the staged pitching machine, but it is a simpler design mechanically. The upper hold down is fixed at the loading end, and would be constructed

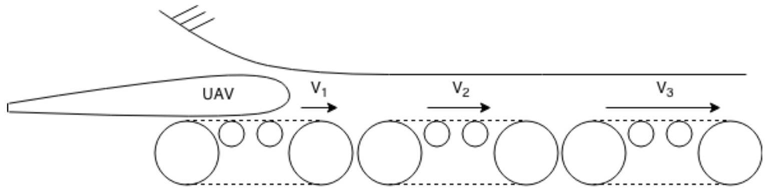

Figure 4.7: Side View of Simplified Progressive Pitching Machine Concept

out of a low-friction, flexible material. The intent was for the hold-down to provide adequate downward force but still allow for UAV passage. Even though the sytem was simplified, the stakeholders were still leery of using three motors. However, this concept is what opened the discussion that ultimately led to the selected design.

4.2 Design Selection

Until this stage of concept development, consideration had not been given to exploring the possibility of an electric motor starting from rest and accelerating the UAV. Along this line of thought, the concept shown in Figure 4.8 was developed.

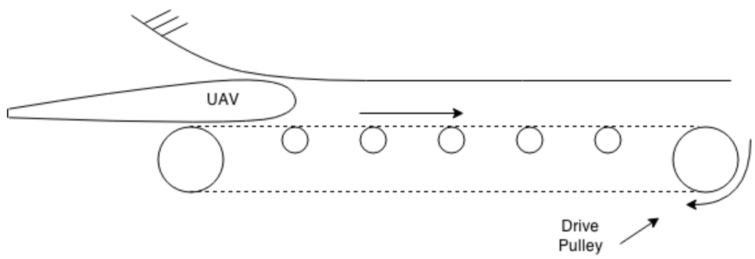

Figure 4.8: Side View of Single Motor Pitching Machine Concept

The operational concept for this design was to load the UAV with no power applied to the drive motor. Once loaded, power would be provided, and the motor would accelerate the aircraft to flying velocity from rest. After the UAV departed the launcher, the motor would be shut off and the conveyor would decelerate back to rest. The process would then be repeated for follow-on launches. Stakeholders were optimistic of the concept, and the decision was made to further explore the design.

The system was initially envisioned to utilize a high-grip conveyor belt as the power-transfer method. However, market research showed that commercially available conveyor belts are not designed for high-speed operation or shock loads.

The next method considered was the use of a timing belt. These are commonly found in automobile applications to transfer power from the motor to various accessories. The environment is both high-speed, and subject to shock-loading due to rapid changes in the motor's power output. Also, timing belts have a high strength-to-weight ratio, making them ideal for this application. Unfortunately, the timing belt idea fell short when requests for information from various manufacturers went unanswered. It was unknown if the use case presented a liability concern, or if they were unable to supply a belt that met requested specifications. This led to the exploration of using roller chain as the power transmission device.

Roller chain was originally discarded due to its relatively high weight compared to belts. However, the use of it opened up a new concept for the UAV attachment method. Rather than use an upper hold-down to generate friction between the belt and UAV, it was thought a 3-D printed interface could be designed that would slide onto the UAV's existing hook and snap into the chain. The concept was for the component to vertically snap in place between the links of the roller chain. This aspect of the system will be discussed in detail in Chapter 5. It was mentioned here because the newfound simplicity afforded by this method was a determining factor for continuing development.

For an initial look at a potential layout for this concept, a baseline CAD model was developed. This is shown in Figure 4.9.

Figure 4.9: CAD Overview of Roller Chain Concept

The system features a single electric motor at the departure end of the launching section. On the upper surface, a low-friction guide is attached to the frame to support the roller chain. The return section, or lower surface, uses a series of idler sprockets to guide the chain. Tensioners are mounted to each end of the assembly for adjustment of the chain tension.

The primary concern with this concept was the availability of a motor that could perform the task. It was reasoned that, if an acceptable motor could be sourced, the system had the potential to meet all stakeholder requirements and remain within the aforementioned construction and design limitations. The key strengths of the concept are:

1. The system is relatively simple from a mechanical viewpoint.
2. The use of an electric motor eliminates the need for extensive support equipment required for pneumatic systems.
3. It was predicted the system would meet Requirements 1-9 for high-level functionality.
4. There is not be an impact at launch. The energy generated during launch is dissipated smoothly over time as the chain decelerates.

CHAPTER 5: Proof-of-Concept

Referring again to the systems engineering (SE) process shown in Figure 6.1, the development effort was now at the bottom point of the V. This chapter outlines the activities associated with maturing a concept into a testable prototype.

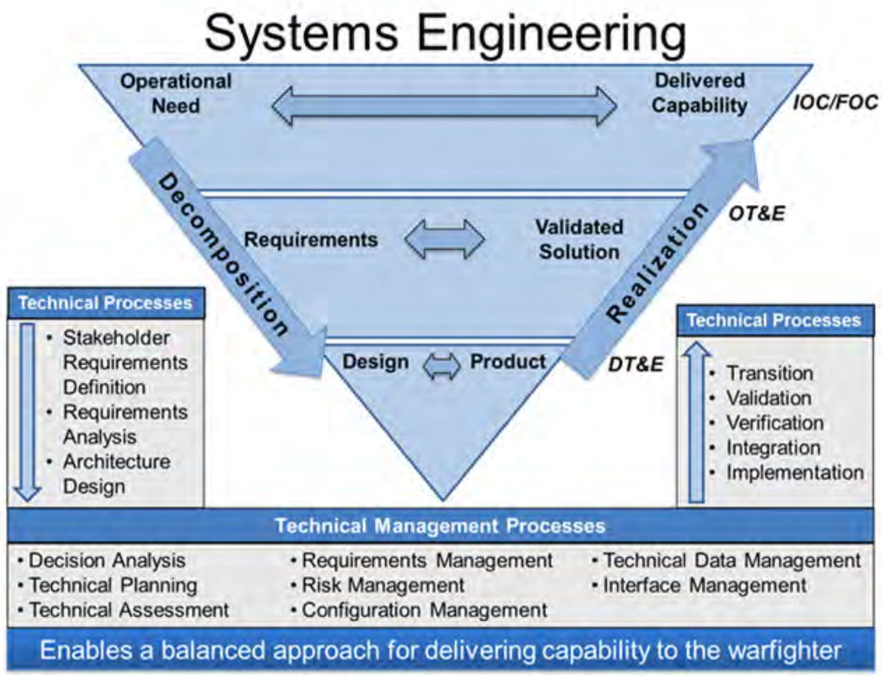

Figure 5.1: DOD SE Process Overview, from [19]

To further explore the feasibility of the chosen concept, a proof-of-concept (POC) needed to be designed and built to study the system characteristics and conduct developmental test and evaluation (DT&E). The purpose of DT&E activities are to support [19]:

- Identify, assess, and mitigate the technical risks.
- Assess the technical performance and system maturity.
- Provide empirical data to validate models and simulations.

All of these points are addressed during POC development as part of the design review. However, the first two require a front-end discussion of the approach methodology.

5.1 Risk Management

Risk identification, risk assessment, and risk mitigation are arguably the most difficult aspects of a development effort to accurately characterize. Identifying risk is challenging because it is a forward-looking statement. It is a prediction used to identify perceived issues that may occur in the future. Predictions inherently imply that some form of data exist to suggest an outcome. At the early phases of development, there are frequently "unknown unknowns," where no data exist to alert the design team of a potential issue. To clarify, an issue is something that has already occurred and must be rectified. The purpose of identifying, assessing, and mitigating risk is to prevent issues. The essential information that risk management provides is:

If This (Identification) This is the process of identifying what future issues may occur. For example: If the motor seizes during a launch cycle, then something will happen.

Then That (Assessment) This is the result of analyzing what would occur should the identified event take place. For example: If the motor seizes during a launch cycle, then the unmanned aerial vehicle (UAV) will fail to launch.

Do This (Mitigate) Risk mitigation addresses what actions will be taken to reduce the likelihood of occurrence or severity of the outcome. For example: The UAV method of attachment will be designed in a way that motor seizure during launch will not cause physical damage to the aircraft.

The accepted DOD approach for portraying risk information is to use a risk matrix like the one shown in Figure 5.2. The vertical axis portrays the likelihood of occurrence based on percentages. The horizontal axis represents the severity of the consequence should the risk event occur.

There are three primary types of risk: Technical Performance, Schedule, and Cost [30]. *The Department of Defense Risk Management Guide for Acquisition Programs* suggests that acceptable levels of risk should be tailored to the constraints and objectives of each program [30]. For this effort, the primary area of concern was technical performance risk. This is not to say schedule and cost risks were not assessed and managed throughout the process. Schedule, in particular, is mentioned numerous times throughout prototype development. However, the central focus of this effort was to demonstrate a new technical

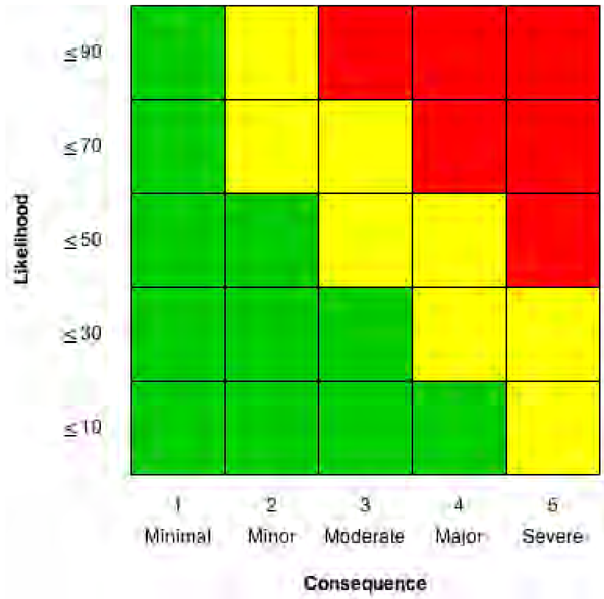

Figure 5.2: DOD Standard Risk Matrix, after [30]

capability. As previously mentioned, limited human resources mandated a reduction in scope for certain aspects of the SE process. The written guidelines for technical consequence definitions are shown in Table 5.1.

Table 5.1: Technical Risk Consequence Definitions, from [30]

Level	Technical Performance
1	Minimal or no consequence to technical performance
2	Minor reduction in technical performance or supportability; can be tolerated with little or no impact on program
3	Moderate reduction in technical performance or supportability with limited impact on program objectives
4	Significant degradation in technical performance or major shortfall in supportability; may jeopardize program success
5	Severe degradation in technical performance; cannot meet KPP or key technical/supportability threshold; will jeopardize program success

For determining the likelihood and consequence of various technical risks, there usually exists a full team of individuals assigned specifically to this task. Team collaboration helps to mitigate the subjective nature of this effort. In this case, the stakeholders were used for this purpose.

Various methods were used to mitigate and manage risk, and these will be discussed throughout the development, but the ultimate remedy is knowledge. As subsystems are developed and tested, previously unknown information about the system is gained. Definitively knowing how a system will respond in all scenarios is the elimination of all risk. This, however, is not possible and can never be fully realized. Rather, the effort is to understand as much as is feasible, and apply that knowledge at each phase going forward. The purpose of iterative prototyping is to allow for progressive design modifications, as risk is understood. The objective is to identify and mitigate the risks that fell under a red classification first as identified in Figure 5.3, as these posed the greatest threat to success. At completion of the research, the goal was for all technical risks to fall under a green classification.

At the onset of POC development, there were two primary risks to be addressed. First, the power required was unknown – which brought into question the availability of a motor that could meet specifications. Second, it was unknown if the roller-chain could be properly supported in a manner that still allowed for UAV attachment. These risks were assigned as shown in Figure 5.3.

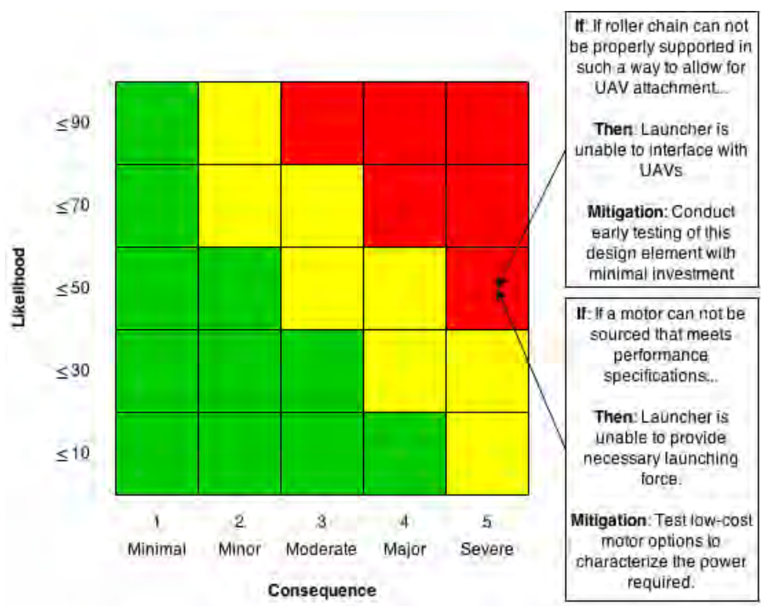

Figure 5.3: High-Priority Design Risks, after [30]

5.2 Technical Performance and System Maturity

Technical Readiness Level (TRL) assessment is the standard metric used by DOD programs to characterize the technical maturity of a system [19]. The nine TRL levels and accompanying definitions are show in Table 5.2. The goal was to reach TRL 7. TRLs define the system maturity; while performance is measured against requirement thresholds and objectives. This process is how systems are verified and validated to ensure they are meeting performance specifications, while also satisfying the operational goals.

Table 5.2: TRL Overview, after [31], [19]

TRL	Definition	DOD DAG Description	Supporting Information
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
4	Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
5	Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.	Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
7	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space.	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.	Operational Test and Evaluation reports.

The research completed thus far in the study satisfies the requirements for TRL 1. As the POC is developed, the intermediate goal is to accomplish a TRL of 5 prior to building the follow-on prototype.

5.3 Proof-of-Concept 1

The final prototype is the result of over 100 individual component iterations. As is common with integrated systems, the alteration of one subsystem usually results in the modification of many others to satisfy interactions within the system. If presented outside the context of the integrated system, the evolutions of a single component are difficult to convey without confusion. To alleviate this, the final iteration of each concept is presented first, followed by the chronological component evolution that led to the end product. For tracking purposes, significant changes to the system are referred to as numbered versions. The POC is broken into four versions, POC-1 through POC-4.

The reader will note multiple, future references to a "prototype." To avoid confusion, the proofs-of-concept were wood-framed mockups used as stepping-stones to later develop a usable, long-term prototype. The POCs were never intended for long-term use by ARSENL. On that note, most of the discussed design decisions and calculations were driven towards the eventual prototype development, not the POC.

5.3.1 Overview

An overview of POC-1 is shown in Figure 5.4. Note that fasteners, the roller chain, and power transfer belts were not modeled in the computer-aided design (CAD). The prototype's frame was constructed out of readily available 2X4 pine lumber. Functionally, it operated in a similar fashion to the final concept discussed in Chapter 4.

The rear and front sides feature a six-inch diameter, quick-disconnect sprocket sized for ANSI 40 roller chain. The sprocket is supported by a one-inch, steel drive shaft, mounted on split-case, pillow-block bearings. Bearings are attached to adjustable, stainless steel conveyer-belt tensioners that are through-bolted to the wood frame. Two PVC pipes run the length of the launcher as support rails for the UAV.

For clarity, a close view of the front side is shown in Figure 5.5. For POC-1, a small

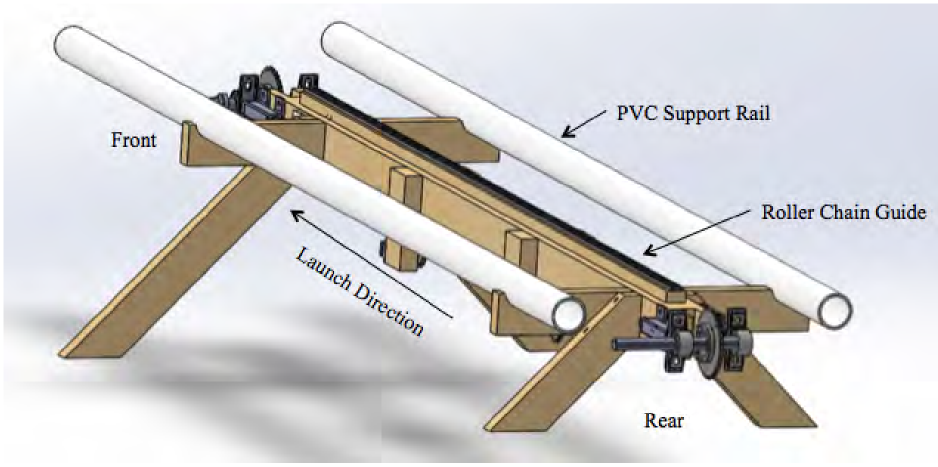

Figure 5.4: POC-1 Overview

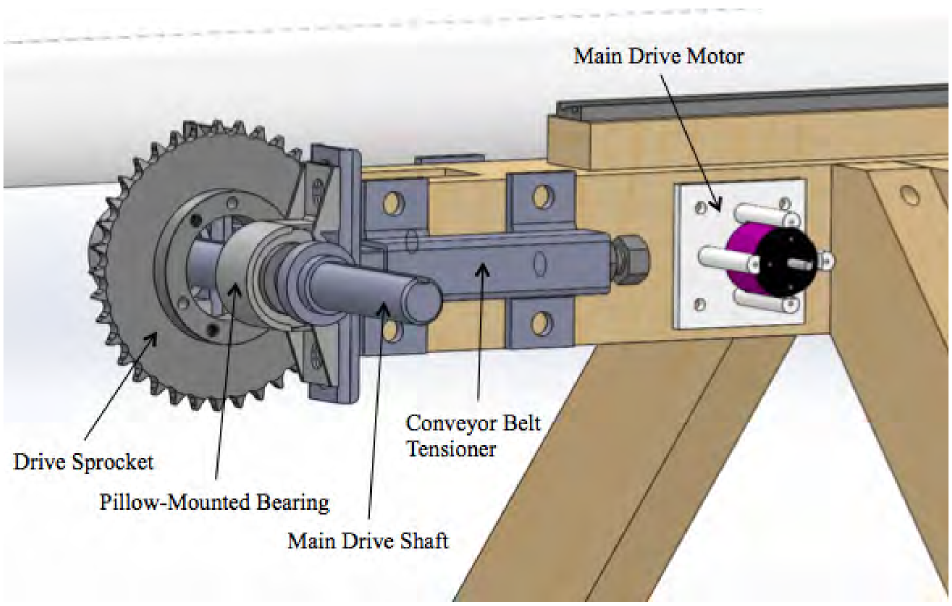

Figure 5.5: POC-1 Front Detail

motor typically used in remote control aircraft applications is mounted with a gearing ratio of 60:9. Power transfer from the motor to the driving sprocket is accomplished with a miniature timing belt (not shown in the CAD).

UAV attachment is accomplished via a 3-D printed interface. A front-quarter view of this component is shown in Figure 5.6. The piece is removable from the UAV for legacy launcher compatibility, satisfying Requirement 6 (R6). The component slides onto the

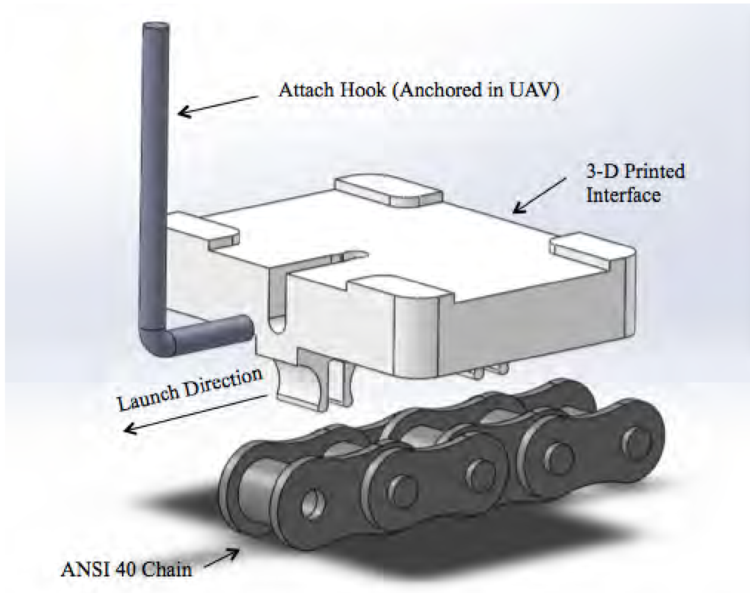

Figure 5.6: 3-D Printed UAV Interface

UAV's hook and is clipped in place as the hook passes a pinch point in the channel. After attaching it to the aircraft, downward pressure is applied with the clip in position over the roller chain. The pegs on the bottom of the 3-D component then clip into the roller chain for UAV attachment. It requires approximately five pounds of vertical force to insert or release the interface from the chain. The method of release concept for this component is for the teeth of the front drive sprocket to automatically eject the interface, thereby detaching the UAV from the chain.

5.3.2 Roller Chain and UAV Interface Design

To comply with the previously discussed risk mitigation plan, the first components of interest were the roller chain and the UAV interface. These were not trivial design tasks. Commencing with the roller chain, extensive research was required to design the system.

To give the reader an accurate perspective of the complexity of this task, a single manufacturer, Rexnord, produces 5,000 variants of roller chain solutions [32]. To limit the sizing options, it was decided to work with the standard American National Standards Institute (ANSI) chain sizes available in the United States. This scale ranges from ANSI 25 to ANSI 240. The ultimate tensile strength of these chains is 780 and 112,500 pounds respectively [33]. For reference, ANSI 35 chain is approximately the size used for most bicycles. Rexnord's chain guide provided information that showed chain sizing and RPM of the drive sprocket are directly related. Smaller chains are better suited for higher RPMs (the dependence of this measurement on RPM also affected the sprocket sizing, discussed later) [32]. If load requirements dictated higher tensile strength than the appropriate chain size could provide, chains may be constructed in parallel strands (attached side-by-side).

Requirement 18 (R18), dictate no more than 20 pounds of force be applied to the UAV hook. On the five pound UAV, this translates to a 4g acceleration limit. The working load (less than the ultimate tensile strength) for ANSI 25 chain is 140 pounds [33]. So, assuming friction and tension loading are minimal, even the smallest chain provides a safety factor of 7.0. The goal was to use the smallest, technically acceptable solution. However, the dimensions of this chain were so small that it was reasoned a UAV interface would not be able to clip with enough holding force to launch the aircraft. It was decided that one size up from ANSI 25 should suffice; therefore, a three-foot section of ANSI 35 chain was ordered with an idler sprocket for testing. An idler sprocket is a smaller, free-spinning, sprocket used for chain alignment and support.

Having selected a size for the chain, the UAV interface was designed. The on-hand availability of 3-D printing made it a relatively straightforward task. The goal was to make a basic prototype into which the UAV's hook could slide with attachment prongs sized for the chain. Two images of the CAD, one sectioned for clarity, are shown in Figure 5.7 and Figure 5.8.

The tests consisted of two parts. The first was to see if tolerances were accurate for the hook sliding into the interface. These were found to be too tight, and were adjusted in follow-on versions. The second set of tests was to observe how the interface interacted with the chain. The tests performed and qualities examined were:

- A snap-in test was performed to determine if tactile or audible feedback were present to indicate the clip was secure in the chain.
- A pull-off test followed to observe the force required to remove the clip from the chain.
- The chain, with clip attached, was then pulled over the sprocket to determine if the teeth would eject the interface.

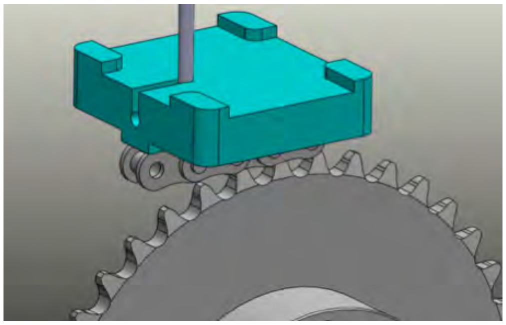

Figure 5.7: CAD of First UAV Interface

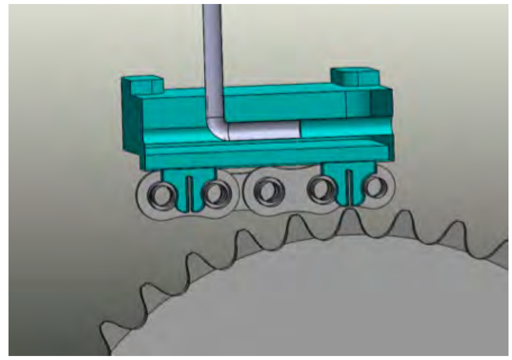

Figure 5.8: CAD of First UAV Interface (Sectioned)

These tests revealed that ANSI 35 chain was also too small. The snap-in functionality of the interface did not work well with the chain. The issue was a balance of how much material could be removed from the pegs that inserted into the chain. This concept is illustrated in Figure 5.9.

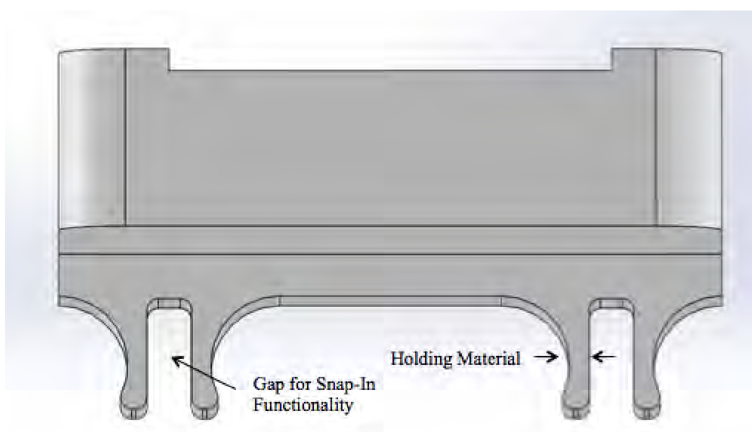

Figure 5.9: Expanded UAV Interface

The width of the gap determines how much flex the pegs have when being inserted into the chain. The problem with ANSI 35 chain is that, when the correct amount of material is removed from the clip to insert properly, there is not enough holding material remaining. On a positive note, testing revealed the kick-out functionality using a sprocket appeared to work well. As a result of this testing, the decision was made to increase the size of chain to ANSI 40. For brevity, further mention of the chain sizing is reduced to include only the series number.

Standard 40-series roller chain has a working load of 810 pounds with a weight of approximately 0.4 pounds per foot [33]. The maximum allowable drive sprocket RPM for this series is 8,000 with a normal limit of 6,000 [32]. These specifications were well within the limits of the design, and they allowed for considerable flexibility in the sprocket sizing to achieve a linear chain velocity of 35 mph (R13). In addition to meeting performance requirements, attachment links were readily available for 40 series chain.

Attachments are a single link that can be inserted into the chain with plates protruding in various configurations for mounting attachments. Should the UAV interface fail, using attachments allowed for a risk mitigation alternative. If an issue were to arise, it was reasoned the ability to bolt an adaptor to the chain would allow for enough flexibility in the interface design to solve an issue.

5.3.3 Sprocket Sizing and Configuration

Roller chains are typically used in either power transmission or conveyor applications. Power transmission designs are intended for high-speed shock loads with a short distance between sprockets. Conveyor applications are for low-speed, smooth operation over long distances. This became the first concern with designing the drive – the launcher required a hybrid of both. It is high-speed with shock loading but has a long distance between drive sprockets.

The manufacturer-recommended support structure for high-speed rolling chain is to have a maximum distance between shafts of 20 times the pitch of the chain [34]. This was to control resonance in the chain and prolong its useful life. For 40-series chain, the pitch distance is 0.50 inches [32]. This requires that idler sprockets be placed every 10 inches along the return side of the span. The return, or slack, side refers to the bottom of a horizontally configured roller chain assembly. To satisfy this requirement, an over/under idler configuration was implemented. This configuration, shown in Figure 5.10, uses an alternating high-to-low chain path around the sprockets. The light grey line indicates the chain path.

Figure 5.10: High-to-Low Configuration of Idler Sprockets

Upon review, the stakeholders were concerned about the friction and total system inertia the idler sprockets would add. Configurations that are outside of the manufacturer's recommendations will typically result in reduced life of the chain. However, roller chains have substantial service lives; therefore, the decision was made to reduce the number of idler sprockets. For this POC, only two idler sprockets were ordered. The intent was to observe system characteristics and, if more were necessary, they would be added in follow-on iterations.

For supporting the upper section of chain, a low-friction guide is used. These are precision machined out of ultra-high-molecular-weight polyethylene (UHMW) material to match the roller chain's profile. The necessity for a straight, consistently-supported path along which the UAV would launch eliminated all other options.

Sizing the main sprockets was a function of minimum tooth engagement, and desired linear velocity of the chain. Typically, the drive sprocket (connected to the power source), and the driven sprocket are different diameters. There are ratio limitations established for this scenario, but the POC design allowed for both to be the same diameter. Given the elimination of this factor, the minimum tooth engagement rules were then considered. Rexnord's design guide recommends using sprockets with a minimum of 21 teeth for applications up to 15 m/s (33.6 mph) [32]. It also points out that larger diameter sprockets are better in all respects because they significantly reduce the polygon effect [32]. This effect will not be discussed in detail, but it causes resonance from a velocity imbalance in the chain. For reference, a 30-tooth sprocket has eight-times more efficient than that of an 11-tooth sprocket [33]. Having determined a minimum size of 21 teeth (approximately 3.5 inches in diameter), and established that larger diameters are more efficient, an upper limit needed to be found.

The Rexnord guide suggested that any sprocket from 26 to 40 teeth is the most appropriate choice for highly-stressed, high-revolution applications [32]. At this size range, the "polygon effect is negligible," and "vibration and noise features meet the highest demands" [32]. Sprockets above 45 teeth have reduced take-up capacity which means chains must be replaced at higher intervals [32]. To determine what size should be used between 26 and 45 teeth, the motor source needed to be considered.

It was still unknown what type of motor would be selected for the system. Alternating-current (AC) motors were still a viable option. These motors are designed to operate at maximum, fixed RPM of 1800 and 3600. Direct-current (DC) motors operate at any RPM as a function of supplied voltage; therefore, the limiting consideration for sprocket size was the use of an AC motor. If a direct-drive configuration were used 1800 RPM would be the drive sprocket RPM, with some reduction for load. If gearing reduction were used, a 3600-RPM motor would be chosen and geared appropriately. To satisfy all possible options, the drive sprocket was sized to work with a direct-drive, 1800-RPM motor. A 6.54-inch sprocket at 1800 RPM produces a linear chain velocity of 35 mph. This was the intended size to be used in the prototype, but an error in the order resulted in a 36 tooth, 6.02-inch sprocket being delivered. The plan was to correct the size in follow-on iterations. For now, this was considered acceptable for a POC.

Finally, a method needed to be conceived to adjust the chain tension. Chains will elongate over time, and tension greatly affects the performance of the drive. If it is too tight, and excess friction causes early wear and excessive power draw. If tension is too loose, and chain resonance causes early wear and introduces the potential for derailment. The slack present in the return section measures proper tension. Guidelines dictate this value be equal to four percent of the free-span [34]. To adjust the tension, conveyer-belt tensioners shown in Figure 5.11 were used.

These tensioners have three inches of adjustable travel. They also have an elongated bolt pattern that allows for vertical adjustment in the location of the pillow-block bearings. Combined with left/right positioning of the sprocket on the shaft, virtually unlimited ad-

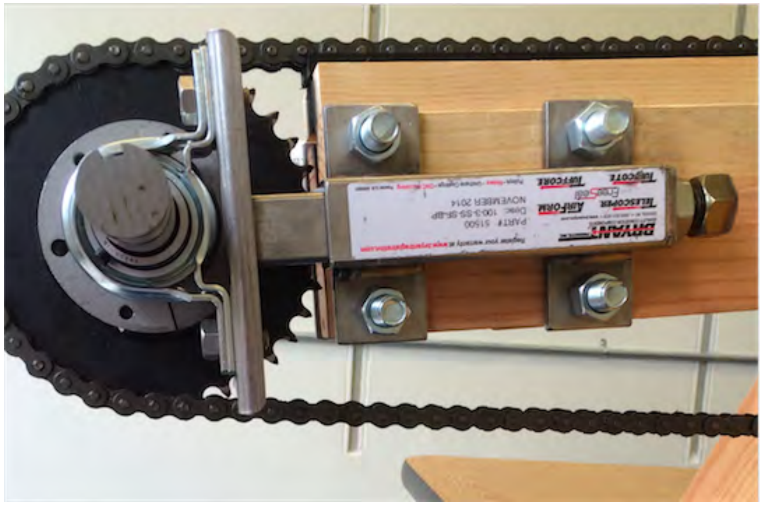

Figure 5.11: Conveyor-Belt Tensioner

justment of sprocket alignment is possible. A graphical depiction of the degrees of freedom is shown in Figure 5.12.

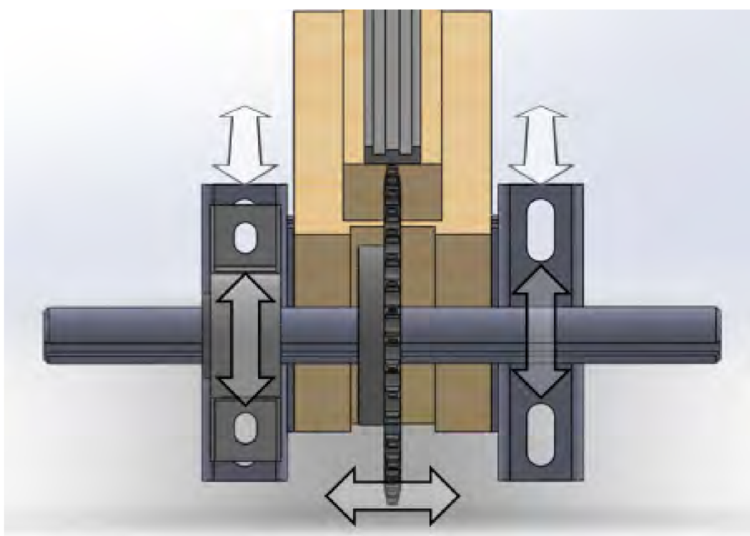

Figure 5.12: Tensioner Degrees of Freedom

From the perspective of a designer, this added welcomed flexibility. From the perspective of the user, this added undesired complexity. Given the importance of sprocket alignment, and the knowledge that a wood frame would not be square, the design team went forward with the tensioner selection. It will later be shown that both parties were correct. These components were needed for the early prototypes, but adjustment was constant and not practical for the end-user.

5.3.4 Motor Selection

It was known at the time of construction that the motor chosen for POC-1 was undersized. However, Advanced Robotic Systems Engineering Laboratory (ARSENL) had dozens of the motors on hand, it presented a cost-effective way to observe basic motion of the system. The goal was for it to provide enough power to slowly accelerate the system to whatever velocity it could manage. Knowing it had marginal torque for the task, it was geared at 60:9 using pulleys and a miniature-series timing belt. The setup is shown in Figure 5.13. Initial tolerance issues with the drive shafts delayed their installation; therefore, wood dowels were temporarily substituted.

Figure 5.13: Motor and Gearing Setup

Mathematical models of the system had not been calculated, which resulted in a gross underestimate of the torque required. The motor stalled immediately upon power application and was completely unusable. The reason a mathematical model had not been created is discussed during the discussion of POC-2 (Section 5.4).

5.3.5 Structure

Mobility of the system was not a concern for this iteration. The only goal of POC-1 was to verify the sprocket layouts and the UAV interface. With this in mind, a simple saw-horse design shown in Figure 5.14 was constructed. The length was chosen at eight feet based on the available size of on-hand materials. The center section consists of two 2X4s laminated together with relief cuts at either end to clear the main sprockets. Four 2X4s are used to mount the PVC support rails. These are shown horizontally protruding from each side of the center section. Drop-down mounts used to secure the idler sprockets are attached at equal distances from either end. The launch angle was designed to match ARSENL's current launcher at seven degrees of incline.

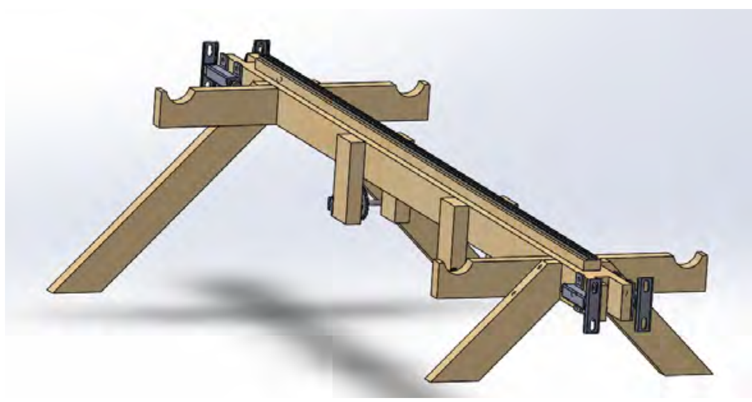

Figure 5.14: POC-1 Frame

The shaft diameter for the main sprockets was chosen at one inch. This is the largest available diameter for which finish-bore sprockets can be ordered, and rigidity was favored over the marginal weight savings of a smaller shaft. Also, high torque would be transmitted via the shaft; hence keyed shafts were selected to absorb the energy. Keyed shafts have a machined relief to insert square stock between the shaft and sprocket. This is to ensure that there is no rotational slippage. The concept is shown in Figure 5.15.

The main bearings selected were inexpensive, split-case bearings that utilize a pillow-block for mounting. They are rated for the desired RPM and load, and allow for a few degrees of shaft misalignment to permit tensioner adjustment. Perfectly rigid bearings would have required both tensioners to be adjusted simultaneously to avoid binding.

When initial assembly of the bearings and shaft was attempted, the shaft was too large to

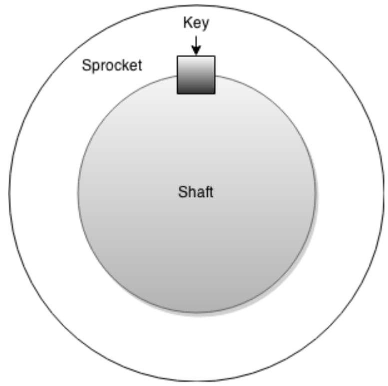

Figure 5.15: Keyed Shaft

fit. Efforts were made to freeze the shaft while heating the bearing, but this also failed. Tolerances for both were correct during the ordering process, but it was discovered that the process of machining the key relief could sometimes compress the component out of true round. A replacement order was placed for certified shafts with tighter tolerances, and the issue was eliminated.

5.3.6 Findings and Recommendations

From the perspective of reducing the motor availability risk, POC-1 was unable to offer any insight due to the undersized motor. However, moving the chain assembly by hand did confirm the UAV interface was ejecting as desired. Also, the following engineering lessons were learned and applied going forward:

Roller Chain and UAV Interface

- It appeared that ANSI 40 roller chain was an appropriate size for the UAV interface. The increased pitch from ANSI 35 allowed for more support material in the peg, while still providing a favorable clipping action when inserted into the chain.
- The stakeholders were pleased with the concept designed for the UAV interface. However, the request was made to reduce the volume and streamline the component. 3-D printed parts are priced by volume; hence a reduction in volume is also a cost-savings. Additionally, the time required to print the component is reduced. Streamlining the part was an aerodynamic consideration because the

interface remains attached to the UAV during flight.

Sprocket Sizing and Configuration

- The six-inch main sprockets were ordered with a quick-disconnect hub. This is a two-part design where the hub and sprocket are bolted together. From a cost perspective, the hub is inexpensive compared to the sprocket. If the shaft diameter changed in follow-on prototypes, replacing the hub would be lower cost than ordering a new sprocket. While the reasoning was sound, the application was not ideal. These hubs are mated to a sprocket using a tapered compression fit. To correctly seat this type of mate, the fastening screws must be methodically tightened to precise torques. It was a cumbersome process and was later removed from the design.
- Conclusions were not possible on the layout of the sprockets until an adequate motor could be acquired and installed. This became the top priority for POC-2.
- Upon receiving the tensioners, it was noticed that there was a significant amount of play in the vertical and horizontal axis of the bracket. This was probably not an issue for a conveyor belt, but for the sprocket assembly, it was unacceptable. Shims were used to temporarily address the issue, but it was clear a better solution would be needed.

Motor Selection

- It was thought gearing ratios could be used to compensate for an under-powered motor. The mechanical theory is sound from a mathematical approach where torque is inversely proportional to speed. However, the electro-mechanical physics of an electric motor impose an entirely different set of limitations that were not considered. While the application was a failure, this realization played a critical role in motor selection for future prototypes.

Structure

- The structure functioned well and as intended. It would remain unchanged for POC-2.

5.4 Proof-of-Concept 2

The second version of the POC focused on modeling the system and selecting a motor source. While that effort was occurring, another temporary power source was acquired to observe the roller chain in motion and analyze sprocket layout. The new assembly is shown in Figure 5.16.

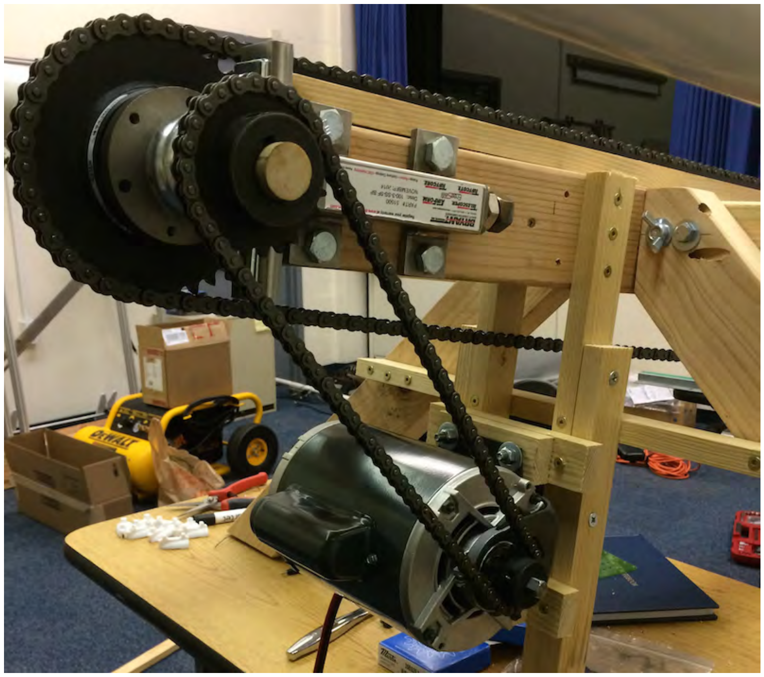

Figure 5.16: POC-2 New Motor Configuration

The team selected a 1/2 HP, AC motor designed to run at 3600 RPM. The on-hand, three-foot section of 35-series chain was repurposed to transfer power to the drive sprocket. The gearing ratio was set at 1.6:1. This equated to an unloaded drive sprocket RPM of 2,250, or 40.16 MPH linear chain velocities. An inexpensive potentiometer designed for AC motors was ordered to adjust the speed of the motor.

The first round of testing for this phase was observational only, and was conducted by applying power to the motor and filming various sections of the chain to observe characteristics. The dual idler sprocket setup appeared to work well with no noticed issues: no derailments of the chain were observed, and the resonance on the return side was minimal.

The second round of testing was focused on gathering analytic data. The values measured were the time it took to accelerate, and the final chain velocity achieved. Chain velocity was determined using high-speed video playback and counting the number of frames it took for a fixed point in the chain to travel one foot. Final velocity was recorded at 36 MPH.

The time required to reach this velocity was highly subjective and relied on audible cues to determine when acceleration was complete. This value was approximately six seconds. Two important conclusions were drawn from this phase of testing:

1. Using a linear acceleration assumption, the time allotted to reach 35 mph on an eight-foot launcher is 0.312 seconds. The motor required six seconds to accomplish this (multiple, full revolutions of the roller chain). This suggested the motor was still significantly underpowered.
2. Even though it took far too long to reach maximum velocity, the 1/2 HP motor showed a final velocity decrease of only 10.4% from the unloaded, theoretical value. This observation, combined with the time taken to accelerate, suggested the dominating torque requirement was due to acceleration of the system rather than steady-state load.

5.4.1 System Modeling

The standard SE approach when designing a new system is to model first, then build prototypes to validate the models. The reader has likely noted the backward process outlined thus far. To explain, the issue preventing the correct order of development was an inability to use any of the roller chain design guides for this purpose. The guides are all based on the premise that a power source had already been selected, and the chain was designed to match the power source – not the other way around. After an exhaustive effort to locate modeling methods for chain, the decision was made to approximate the system with a conveyor belt instead.

Research conducted during the concept development effort uncovered an online calculator used to characterize the inertia and torque required for conveyor belt assemblies. The source can be found at [35]. Although the interactions of belts and pulleys are not equivalent to roller chains and sprockets, the motion and inertial forces present in the systems were thought to be similar. Following this approach, Figure 5.17 shows the terminology used for identifying various inputs needed for the calculation.

Observing the layout of Figure 5.17, it is apparent the configuration is very similar to POC-2. A motor transfers power via primary and secondary pulleys to the main drive. The

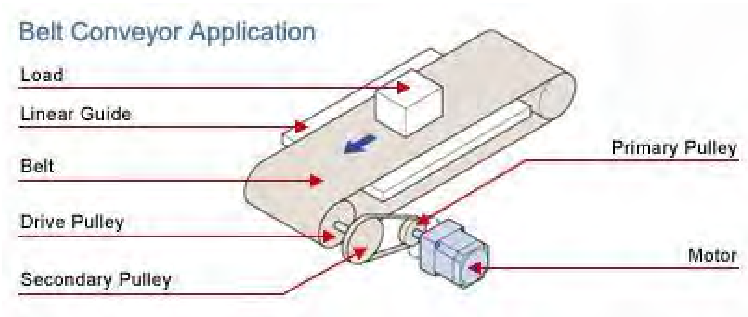

Figure 5.17: Conveyor Components, from [35]

drive pulley then pulls a guided belt to transfer the load. At the time of calculation, it was unknown what the quantitative difference would be between chain and a conveyor belt; however, without an alternative, this was the only viable approach.

The following walk-through of how the model was implemented is based on the physical characteristics of POC-2. Later, the same process would be used to optimize the length and gearing ratios for the system. Figure 5.18 displays the various inputs and values used for the online calculator.

Load and linear guide

Total weight of loads and table	W	=	14.06 [lb]
Friction coefficient of the guide	μ	=	0.05

Drive pulley specifications

Drive pulley diameter	D_p	=	6 [in]
Drive pulley weight	W_p	=	2 [lb/pc]
Number of drive pulleys	n	=	2 [pc]
Efficiency	η	=	95 [%]

External force

F_A	=	0 [lb]

Transmission belt and pulleys or gears

	Primary pulley (gear)			Secondary pulley (gear)		
pitch circle diameter (PCD)	D_{p1}	=	1.99 [in]	D_{p2}	=	3.19 [in]
weight	W_{p1}	=	.5 [lb]	W_{p2}	=	1.5 [lb]

Mechanism Placement

Mechanism angle	α	=	7 [°]

Figure 5.18: Calculation Inputs, from [35]

Total weight was determined by adding the chain weight to that of the UAV. The friction coefficient was estimated for the linear chain guide. Sprocket efficiency was estimated at 95% based on [32]. The remaining inputs have been discussed as elements of the design.

Not shown in Figure 5.18 were the additional calculator inputs for the system to accelerate to 616 inches per second (35 mph) in 0.312 seconds. Finally, a safety factor (or, in this case, margin of error) was selected at 1.5.

Only the results were presented. If the equations are of interest, input the values shown into the online calculator, then open the full report link. Otherwise, the key inputs and outputs are shown in Table 5.3.

Table 5.3: POC-2 Model Results

Parameter	**Value**
Length of Launcher (ft)	8
Launch Time (s)	0.312
g-loading	5.114
Chain Length (ft)	16.8
Chain Weight (lb)	7.06
Chain Weight + Load Weight (lb)	14.06
Load Intertia (oz-in^2)	915.8
Acceleration Torque (in-lb)	187.8
Load Torque (in-lb)	4.75
Total Torque Required (in-lb)	288.8
Required Motor RPM	3145
Motor HP	14.41
Motor Power (kW)	10.75

As previously discussed, the time to launch was calculated using 1-D kinematic equations with a constant acceleration (linear velocity profile) assumption. g-loading for the launch was determined from the change in velocity over time, with respect to the acceleration of gravity. Chain length (CL) was estimated by adding a 10% correction factor to the launcher length (L). This was to account for the idler sprockets and slack in the return line. The equation used is shown for clarity. Note that the drive sprocket radius was initially overlooked in the estimate.

$$CL = \underbrace{2 \cdot L}_{\text{forward and return length}} + \underbrace{0.1 \cdot L}_{\text{correction factor}} \tag{5.1}$$

The online calculator's outputs were load inertia, required torques, and required motor RPM [35]. A motor's HP rating is calculated by multiplying torque output by the RPM of the motor (a constant is also in the equation to correct for units). The most demanding scenario was to assume the motor would be required to output the calculated total torque while at maximum (required) RPM. Motor power expressed in kilowatts is a direct unit conversion from HP. It was only calculated to simplify comparisons with motors that used this unit of measurement over a HP rating.

Recall the initial length for POC-1, and therefore POC-2, was selected because it matched the available length of on-hand materials to construct the frame. With a mathematical model now available to characterize the system, a length sensitivity analysis could be conducted to refine this value.

5.4.2 Length Sensitivity

The purpose for the length sensitivity study was to observe the relationship between acceleration and load torque requirements. For a longer launch section, the acceleration torque decreases (more time is available for the system to reach launch velocity), while the load torque increases (chain weight increases because longer sections are required).

For POC-2, at eight-feet long, the calculator showed acceleration and load torques of 187.8 and 4.75 inch-pounds, respectively. Total torque required of 288.8 inch-pounds was the summation of these values, with the 1.5 safety factor added. As predicted from POC-1 testing, the model showed acceleration torque was the dominating factor. However, the inversely proportional relationship of these torque requirements means that there is an optimal length for the system where total the torque required is minimized. Finding that length, with the hopes it was within design limitations, was the desired outcome for the study.

At the onset of the sensitivity study, two inputs were changed from those shown for POC-2. The primary and secondary sprocket diameters were changed to two and four inches, respectively (the weight estimate remained the same). This enabled the development team to work with a reduction ratio that was easier to manipulate of 2:1 instead of 1.6:1. The analysis was performed by manually entering required acceleration times and chain weights for launcher lengths in one-foot increments from eight to 16 feet long. When it became apparent that the optimal length was beyond 16 feet, the interval was increased to 20 feet. The lowest total torque required occurred somewhere between a 40- and 80-foot launcher length. Since this was well outside of design requirements, a specific length was not found. A summary of the results is shown in Table 5.4.

Even though the minimum torque point was not achievable for this design, the study showed that longer lengths required less torque. As a result, the following observations were made:

1. For the lengths that satisfied trailer length requirements (shorter than 16 feet), longer solutions required less power and exerted lower forces on the UAV.
2. The study confirmed load torque accounted for a very small percentage of the total torque required. This was important because it suggested variances in UAV weights should not significantly affect end-speeds.
3. Launchers shorter than 11 feet exerted too much g on the UAV's hook to satisfy the 20 pound limitation mandated in Requirement 18 (R18).

The study narrowed the range of selection from 12 to 16 feet for the next prototype, but the team still needed justification to select a value within that range. To initiate the process, the 16-foot upper limit was reduced to 14. This was to accommodate any support systems that might extend beyond the actual chain drive. For example, the PVC guide rails on POC-2 were 10 feet long while the chain drive was only eight. The stakeholders requested the shortest option (11 feet) because it was the smallest and lightest solution. The design team, however, was still concerned about the model's accuracy, and reasoned a longer selection allowed for more flexibility. If the motor chosen were found to have excess power, the length could easily be shortened. The same does not hold not true for lengthening the prototype if it were underpowered. As a tradeoff to satisfy both parties, a mid-point length of 12 feet was selected.

Table 5.4: Length Sensitivity Results

Length of Launcher (ft)	Launch Time (s)	G-Loading	Chain Length (ft)	Chain Weight (lb)	Chain + Load (lb)	Weight Weight	Load Intertia (oz-in2̂)	Acceleration Torque (in-lb)	Load Torque (in-lb)	Total Torque Required (in-lb)*	Required Motor RPM	Motor HP	Motor Power (kW)
8	0.312	5.114	16.8	7.06	14.06		594.2	152	3.807	233.7	3924	14.55	10.85
9	0.351	4.546	18.9	7.94	14.94		625.8	142.3	4.046	219.6	3924	13.67	10.20
10	0.390	4.091	21	8.82	15.82		657.5	134.6	4.284	210.2	3924	13.09	9.76
11	0.429	3.719	23.1	9.70	16.70		689.2	128.2	4.522	199.2	3924	12.40	9.25
12	0.468	3.409	25.2	10.58	17.58		720.9	123	4.76	191.6	3924	11.93	8.90
13	0.507	3.147	27.3	11.47	18.47		752.9	118.5	5.001	185.3	3924	11.54	8.60
14	0.545	2.922	29.4	12.35	19.35		784.6	114.9	5.24	180.2	3924	11.22	8.37
15	0.584	2.728	31.5	13.23	20.23		816.3	111.6	5.478	175.6	3924	10.93	8.15
16	0.623	2.557	33.6	14.11	21.11		848	108.7	5.716	171.6	3924	10.68	7.97
20	0.779	2.046	42	17.64	24.64		975	99.92	6.672	159.9	3924	9.96	7.42
40	1.559	1.023	84	35.28	42.28		1610	82.44	11.45	140.8	3924	8.77	6.54
60	2.338	0.682	126	52.92	59.92		2245	76.66	16.23	139.3	3924	8.67	6.47
80	3.117	0.511	168	70.56	77.56		2880	73.76	21	142.1	3924	8.85	6.60

(*1.5 Safety Factor)

5.4.3 Motor Selection

For a 12-foot launcher, the online calculator showed that an 11.93 HP (8.9 kW) motor was required. The total torque requirement was 191.6 inch-pounds. Using these values to initiate the search, the following observations were made:

- AC motors that produce 10-12 HP are all powered on a 220V or 3-phase circuit. This is not an available power source at the ARSENL testing facility. For this reason, the use of an AC motor was eliminated from further consideration.
- DC motors in the 10-12 HP range require battery arrays for power. The other option would have been to use a DC power supply; however, an 8.9 kW motor intuitively requires an 8.9 kW power supply. Similar to the issue with AC motors, 8.9 kw power supplies require an input voltage of 220V or 3-phase.
- Batteries, unlike power supplies, are able to provide extremely high currents (up to 1100 amps on high-discharge, lead-acid cells). Also, the current is available at any voltage by wiring cells in series. It became clear that this would be the ideal solution to power the launcher motor. Other benefits include:
  - Full mobility of the system without a power chord.
  - A battery array for the main drive motor could also provide a stable source of DC energy for on-board sensors and processors.

The primary concern with using a battery array was the weight. The expected high-current draw required for launch necessitates the use of high-capacity batteries that can provide 50 launches without recharge. Higher-capacity batteries are larger and heavier. Also, the number of batteries required (voltage requirement for the motor) was still unknown. This, however, was the only available option; thus work on this solution continued with an emphasis on minimizing weight.

Having established that a DC motor was the only viable option, the motor selection process turned towards the selection of a brushed or brushless option. A brushless motor, as the name implies, does not use a brush/split-ring commutator design to generate the fluctuating magnetic field required for operation. Without getting into the specifics of the design differences, the considerations to the user are:

Brushless Motors

1. Brushes are essentially the only element of a DC motor that requires interval replacement. Removing these all but eliminates motor maintenance. As a result, brushless motors also tend to last longer than their brushed counterparts.
2. Brushless motors run quieter and smoother due to contactless control of the motor's RPM. This means they are more efficient.
3. These motors require sophisticated speed controllers to electronically switch the current without brushes. Speed controllers add cost and complexity to the design.

Brushed Motors

1. For brushed motors, speed controllers are not necessary; the brushes accomplish the same task mechanically. Elimination of a speed controller reduces system complexity and cost.
2. A speed controller, like any electronic component, has internal resistance. This has a negative impact on power available to the motor. For applications where a surge of high starting-current is desired (high torque), brushed motors are ideal.

Given that brushed, DC motors are the better and simpler option from a performance perspective, this was the selection made. The use of standard search-engine techniques to find motors in this HP range did not return useful results. Rather, the author turned to websites targeted at modified, high-performance golf-carts. Motors used for these vehicles are in the power range required for the launcher. Of the available manufacturers, Motenergy presented the best HP for cost. Two of their motors met the performance requirements, the ME1003 and the ME1004. The motors' specifications are shown in Table 5.5.

In some cases, more power is better. However, when acceleration time for an electric motor is key, the correct amount of power is critical. To explain why that is, imagine the installation of a low-speed, high-torque electric motor designed for trains. It would certainly satisfy the torque and HP requirements, but the high armature inertia inherent with high-torque motors would take far too long to accelerate. At the other end of the spectrum, a high-rpm motor that derives its horsepower from RPM, rather than torque, could be installed with a gear reduction. These motors accelerate almost instantly due to their low armature inertia. This former was the attempted application in POC-1. Knowing

Table 5.5: Motenergy Motor Specifications

Specification	ME1003	ME1004
HP Continuous	15.4	10.75
HP Peak	30.8	21.0
Voltage	72 Volts	48 Volts
Speed	3700 RPM @ 72V, Unloaded	3700 RPM @ 48V, Unloaded
Size	8” Diameter, 7.4” long	8” Diameter, 6.4” long
Weight (Pounds)	39	32
Armature Inertia (oz-in^2)	1464	1093
Rated Torque (in-lb)	336.3	214.4
Stall Torque (in-lb)	955.8	610.56

that it did not work, and reasoning that an excessively oversized motor would also not work, research was conducted to determine what the optimal answer should be.

A 1998 presentation given by Richard Armstrong on load-to-motor inertia mismatch holds the answer. In his study, it is shown that the optimal load-to-rotor inertia ratio for acceleration and positioning is 1:1 [36]. The maximum suggested ratio is 10:1. On a simplified level, the reason behind this is because small motors with low rotor inertias have a difficult time producing motion in a higher inertia system. Alternatively, a motor with substantially higher rotor inertia has little difficulty with the system, but the motor must now overcome its own internal inertia.

The findings in the presentation suggested the ME1003 was not only overkill for the system, but it would also degrade the acceleration performance. Additionally, the ME1003 required a 72 Volt power source. In comparison to the ME1004, that is the addition of two extra batteries, and the weight penalty was undesired. Therefore, an order was placed for the ME1004 to be implemented in POC-3. Also, the sprocket sizing was adjusted to optimize the system.

5.4.4 Sprocket Optimization

The characteristics of the system, as configured in POC-2, and the motor are shown side-by-side in Table 5.6

As this discussion commences, it should be mentioned that the duty cycle for peak HP

Table 5.6: System and Motor Characteristics

Specification	ME1004	POC-2 Chain Assembly
HP Continuous/Peak	10.75/ 21.0	14.41
Speed	3700 RPM @ 48V, Unloaded	3924
Armature Inertia (oz-in^2)	1093	720.9
Rated/Stall Torque (in-lb)	214.4 / 610.56	191.6

and twice the rated torque is five minutes continuous. With an expected duty cycle of 0.4 seconds on, followed by 18 seconds off, peak values were usable power figures without harming the motor.

The online conveyor belt calculator was again used to adjust sprocket sizing to match the system with the selected ME1004 motor. Adjustments were made to the drive, primary, and secondary sprocket diameters. The goal was to reduce the RPM requirement and match the load-to-rotor inertia while remaining within the motor's power and torque limitations.

The chosen configuration for follow-on iterations was 7-inch drive sprockets with a 2:1 gearing ratio (primary and secondary sprocket diameters of two and four inches, respectively). This produced the changes shown in Table 5.7. The components for these changes would be ordered, but did not arrive in time for POC-3. The sprocket changes would not be implemented until POC-4.

Table 5.7: Modified System and Motor Characteristics

Specification	ME1004	Modified Chain Assembly
HP Continuous/Peak	10.75/ 21.0	14.75
Speed	3700 RPM @ 48V, Unloaded	3227
Armature Inertia (oz-in^2)	1093	975.4
Rated/Stall Torque (in-lb)	214.4 / 610.56	386.3

Notice the HP requirement increases from the configuration used in POC-2, but the inertia ratio of the motor and the chain assembly is nearly 1:1. Also, the RPM requirement for the chain is reduced to 3,227. This allows for an 11.4% reduction in the motor's available RPM to account for loading.

5.4.5 Battery Sizing

Next, an appropriate battery array needed to be ordered for the motor. Knowing the expected torque requirement was 386.3 oz-in^2, the predicted current was calculated based on the motor's torque constant (this relates torque to amperage with units of in-lbs/amp). This value was found to be 346.4 amps. This high current-rating rules out most battery chemistries, with the exception of lead-acid. Often listed as Pb (lead), these batteries are considerably heavier than their lithium-polymer (LiPo) counterparts, but the allowable discharge rate is much greater. They are also less expensive.

Knowing the expected discharge current and the time of discharge, the team could derive the required battery capacity. For a conservative discharge time of 0.5 seconds at 350 amps for 50 launches, the battery capacity consumed would be 2.43 amp-hours (Ah). The rate of discharge is directly related to battery capacity, and the minimum capacity capable of a 350-amp discharge rate occurs at approximately 17 Ah capacity batteries. The batteries selected have a 22 amp-hour capacity with a 750-amp discharge rating. Using the same assumptions for current draw, these batteries are capable of providing approximately 450 launches before recharge. They are also relatively lightweight for a Pb battery at 14.5 pounds apiece. Four were ordered and wired in series for a total of 48 Volts.

5.5 Proof-of-Concept 3

POC-3 was the first concept that utilized a power source capable of launching the UAV. This was the first concept capable of meeting all launching-related performance requirements. A CAD overview of the system is shown in Figure 5.19, and a close-up of the supporting structure for the motor is shown in Figure 5.20.

5.5.1 Testing

All tests for POC-3 were conducted in a laboratory setting. Retired Zephyr aircraft were used for launching tests, which allowed the team to push the envelope in terms of g-loading and other forces exerted on the aircraft. The methodology and elements tested were:

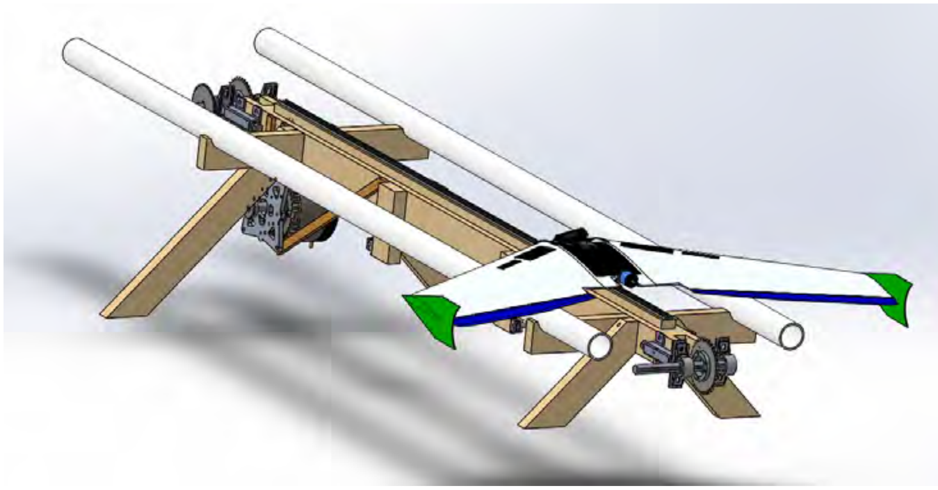

Figure 5.19: POC-3 Overview with UAV

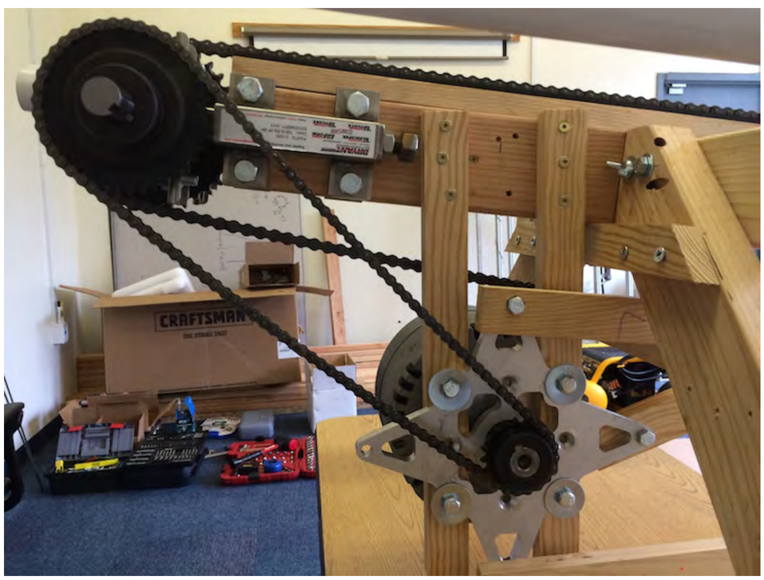

Figure 5.20: POC-3 Motor Mount

UAV Interface

1. The interface was tested for its ability to transfer power from the chain to the UAV (R16). The test was performed by attaching the interface to the aircraft, and then clipping the interface into the chain. Power was applied to the system, but the voltage was limited to reduce end-speed. Once it could be verified that the system was operating safely, the voltage limits were progressively raised

until the full 48 Volts were applied. However, the UAV was not attached for tests conducted above 24 Volts. Launching the UAV at full-velocity indoors was not an option.

2. It was also desired to determine what pitching moments, if any, were generated during ejection of the interface from the chain (R17). Conducted in the same series of tests at 12 and 24 Volts, high-speed cameras were used to record the UAV at the departure end. Playback results were then analyzed.

Motor Selection

1. To alleviate the highest risk element and greatest unknown, it was desired to validate that the motor was capable of generating the necessary power for launch (R1, R13). For this, velocity profiles were recorded at the full 48 Volts to determine chain speed.
2. The real-time current was measured to compare tested results with theoretical values. These were used to validate the mathematical model of the system.

The testing results, along with mitigating design changes, are presented by component in the following sub-sections.

5.5.2 Motor Results and Model Verification

It was encouraging the first time power was applied to the motor. Even though the initial series of tests were safety-limited to 12 volts (low velocity), the motor showed no signs of hesitation. To the naked eye, acceleration was instant. There was not a throttle implemented for these tests, power was applied via a contactor (an electrically-controlled switch that provides on/off functionality for high-current systems), and the motor pulled as many amps as were necessary to reach maximum RPM. For a launcher application, this should have been the ideal setup – maximum power as quickly as possible. However, further testing would show this was not an accurate prediction.

Motor voltages applied were progressively increased in 12-volt increments until the full 48 volts was reached. Peak amperages of each test were recorded for model verification, and high-speed film was captured to analyze the velocity profile of the chain during launch. It was initially noticed that the ammeter was measuring amperages far greater than expected. The model had shown that an eight-foot launcher should require 233.7 in-lbs of torque.

Factoring out the 1.5 safety margin, this becomes 155.8 in-lbs. Using the torque constant for the motor, the system should have required 140 amps, but the test showed that 437 amps were drawn.

At first, it was assumed that the online calculator used to model the launcher was a poor approximation of the system. Then, video analysis showed the motor was accelerating the chain to design velocity in only three feet. Therefore, the constant acceleration assumption used for the timing input in the online calculator was not accurate.

To correct the model, the analysis was performed on a one-foot section of the launcher rather than the full length. This resulted in the linear assumption being a better approximation. Also, the foot selected for comparison was determined by where the maximum acceleration took place (this was usually the second foot of the launch profile). Logically, the torque required for that foot of motion is what corresponds to the peak amperages that were recorded. With these corrections implemented, the torque requirements calculated by the model were validated with a maximum difference of only six percent from testing results.

Initially, the team was pleased with the motor's ability to accelerate the system. One of the two originally identified high-risk design factors had been eliminated. Unfortunately, the acceleration limit had been exceeded. The motor was capable of launching the aircraft in three feet, but it was generating an average of 16.5g to accomplish this. For a five-pound aircraft, that is 82 pounds of force transferred at the interface attach points. While it was never tested, it was reasonable to assume this amount of force would cause structural failure of the foam wing.

To solve the issue, speed controllers had to be implemented. The selected controller provided up to 300 amps of continuous current. The now validated model for the twelve-foot prototype indicated 213 amps would be required. Therefore, it was reasoned a 300-amp controller should be sufficient. It was slightly undersized for the amperage requirements on the eight-foot POC, but the end-speed was electronically limited to lower the amperage requirements and accommodate testing. The net result from a performance viewpoint was that acceleration was now constant, and the g-loading was reduced to acceptable levels.

5.5.3 Interface Results

The UAV interface was not able to provide adequate holding power for launch. Immediately upon power application, the interface pulled out of the chain. Modifications to the interface were delayed until the speed controller was received. It was reasoned the speed controller might reduce the initial jolt sufficiently enough for the clip to work. Upon arrival of the controller, testing showed the high-impulse start was reduced, but the clip still pulled out. Several design changes were attempted to mitigate the issue, but all were unsuccessful until attachments were added. The evolution of these modifications is shown in Figure 5.21.

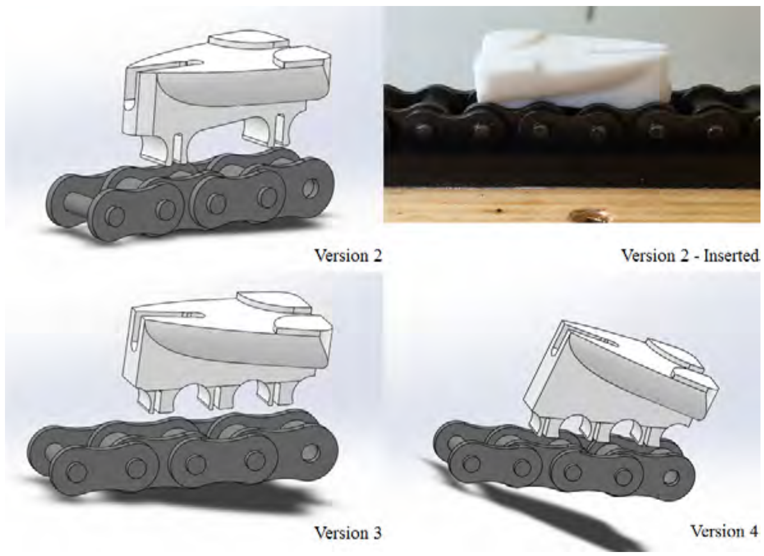

Figure 5.21: UAV Interface Versions

Version 2 This was the result of the stakeholders' request to reduce the size and streamline the UAV interface. Notice that the functionality did not change from the interface presented for POC-1.

Version 3 To achieve more holding power, a third prong was added. Also, the gap in the peg was shifted forward. The energy transfer during launch was entirely on the rear face of the pegs. Shifting the gap allowed for the same clip-in functionality while strengthening the chain contact points. These changes, however, were still not adequate.

Version 4 It was noticed during testing that the interface, when attached to the UAV, was not flush with the chain prior to insertion. There was an angle between the UAV hook and chain that was not considered. The version shown in Figure 5.21 was 15 degrees to emphasize the correction that was made. Final value was found to be ten degrees. Although this did improve the interface, correcting the mating angle still did not solve the issue.

At this point, it was determined the risk mitigation plan would need to be implemented, and attachments were added to the chain. These were initially avoided because the clip-in concept did not require positioning of the chain assembly to attach the UAV. Once attachments are added, the UAV will only connect to a single point (where the attachment is) on the chain. Operationally, this meant the attachment would need to be re-positioned to the correct location following each launch. The positioning function would take time, and it also required a speed controller, which is why attachments were avoided. However, as discussed, the same series of tests revealed it would be necessary for launch, as well.

The use of chain attachments allows for virtually unlimited interface design options. The first concept developed is shown in Figure 5.22.

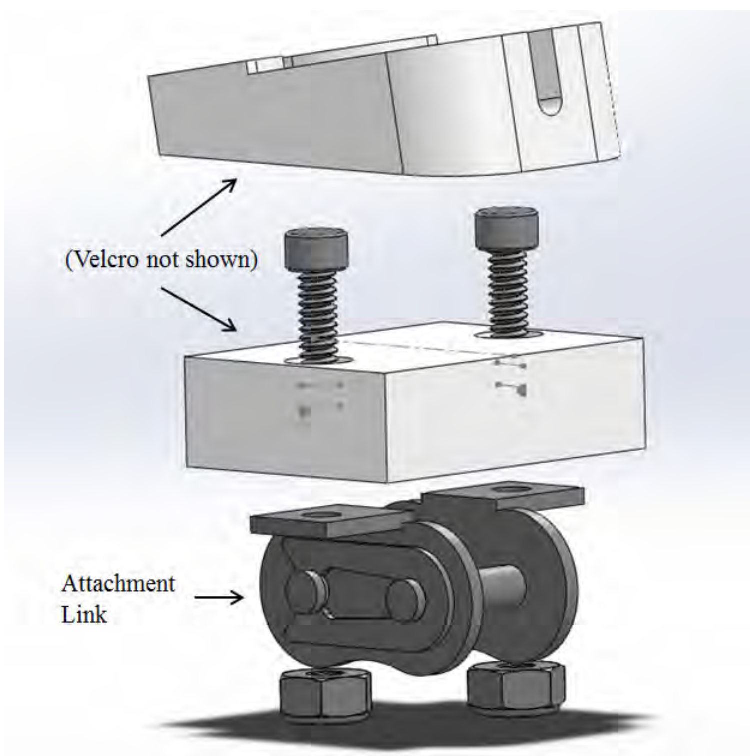

Figure 5.22: Velcro UAV Interface

The Velcro used is a double-mushroom design as opposed to the standard hook-and-loop. This type of Velcro does not quickly wear over time, and it provides an audible and tactile “click” when fully mated. Also, it has a stronger holding force in shear than normal Velcro, which was ideal for the design. Rather than have the sprocket eject the clip as before, the PVC guide rails would support the UAV while the chain rolls away and breaks Velcro contact with the UAV’s interface. A high-speed frame capture from the recorded test series shows the functionality of this concept in Figure 5.23.

Figure 5.23: Velcro UAV Interface Release

It was hoped the Velcro would be sufficiently strong to remain attached during launch. However, testing revealed – just as it did with the clip-in interface – that it would immediately break away during the launch attempt. Another point of contact with the UAV would be required. A stakeholder meeting was held to discuss options, and it was decided that the addition of a wedge interface pushing against the UAV motor mount was the best solution. This change allowed for the wedge to absorb most of the energy transfer, and testing showed the Velcro remained engaged. The reconfigured attachment method is shown in Figure 5.24.

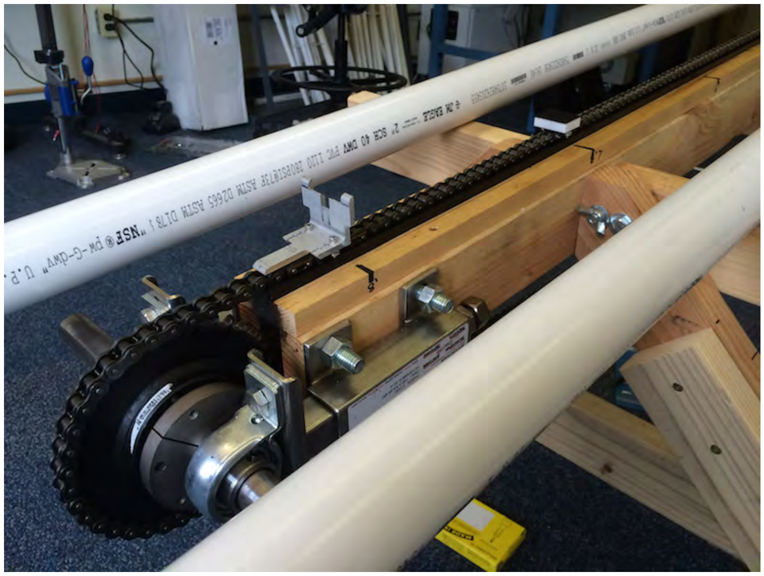

Figure 5.24: Wedge UAV Interface Method

This method proved highly reliable with zero failures during laboratory testing. It should be noted that these tests were conducted at half velocity to facilitate catching of the UAV following the launch. To simulate full-speed tests, the velocity profile was programmed to continue acceleration at the same rate (g-loading on the aircraft and interface), but stop acceleration halfway down the launcher. Also, these tests were able to confirm there was no pitching of the UAV caused by the Velcro release. The PVC support rails were set up to contact the aircraft at the same longitudinal point on the UAV as the nose hold-down. This way, the brief pull-down force experienced during detachment had a moment arm of zero, thereby ensuring it would not pitch the aircraft.

The stakeholders were pleased with the results, and this was the interface design selected for the prototype. A critical design flaw was later revealed, but this issue was not discovered until operational field-testing. It will be discussed in Chapter 6. For now, the interface was functioning as intended.

5.6 Proof-of-Concept 4

One final change was made to the POC prior to full-system testing and prototype development. The total system weight with batteries was over 160 pounds. In accordance with requirements 24-26, motorized wheels were necessary. During the research effort to source a primary drive motor, a wheel-motor manufacturer with an ideal solution had been found. Their geared wheel-motor is designed for a 300-pound robot, and can be controlled with the same type of speed controller used for the launcher motor. The speed controller manufacturer produces a dual-channel version (150 amps per channel), that allows for independent control of each motor. This, in combination with a castoring tail-wheel, allows for a zero-radius turn. The modification, prior to re-mounting the PVC guide rails, is shown in Figure 5.25.

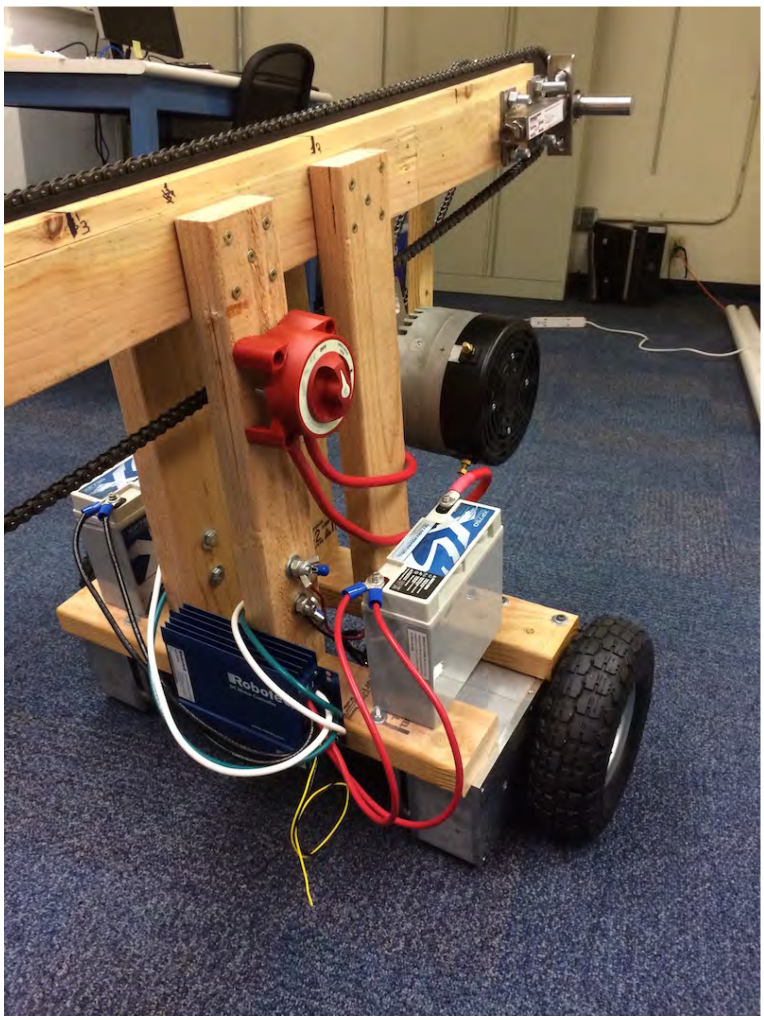

Figure 5.25: Motorized Wheel Integration

The wheel motors added 60 pounds to the design, but the stakeholder desired the afforded functionality that motorized wheels could provide. It would not be implemented in time for the prototype, but motorized wheels, in combination with a wind and heading sensor, would allow for automated wind correction. They also reduce the physical workload of the ground technicians when relocating the system.

5.6.1 Testing

All mechanical aspects of the system were now integrated, which allowed for the first series of tests in a relevant environment. Prior to this, all testing had been conducted in a laboratory. These tests were the first demonstration of the system's ability to launch the UAV at full speed.

Ten launches were scheduled into the testing plan, but only six were accomplished. The motor mount on the UAV was bending as a result of the launch, and on the sixth attempt, the motor mount failed. However, this was not a major concern for the following reasons:

1. The testing environment's close proximity to an airport required the use of a tethered UAV for safety. ARSENL only has one of these in their inventory, and it is in poor condition. The mechanical soundness of the motor mount was in question prior to the tests commencing.
2. The mount itself, which is made out of aluminum angle, is half the thickness as the operational UAVs. Also, it is protruding excessively from the foam support structure. This allows for torque to be transmitted to the foam structure that would not be an issue for the non-tethered aircraft. Figure 5.26 illustrates the difference.
3. The UAV tested in the laboratory has a motor mount that is fully seated in the foam like the operational models. This UAV underwent more than 30 launches at up to 1.5 design load (6g) without bending or failure.

For these reasons, the failure was attributed to the UAV, not the launcher. All other aspects of the launch were favorable.

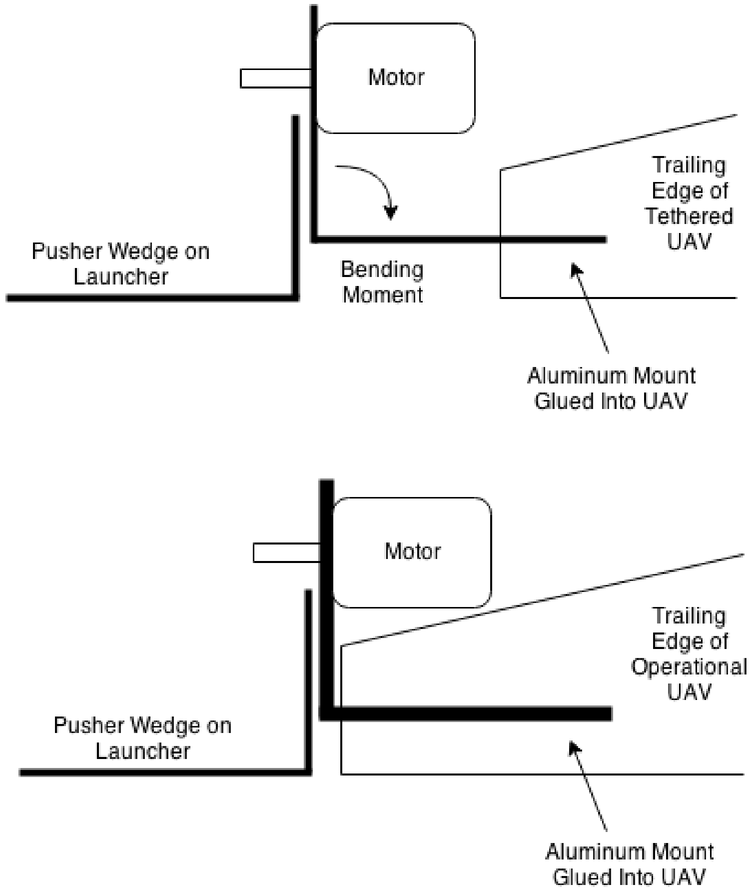

Figure 5.26: UAV Motor Mount Comparison

5.7 Proof-of-Concept System Review

POC-4 marked the completion of the proof-of-concept development effort. Technical risks, system costs, and technology readiness levels were being tracked throughout, but were not specifically presented in the interest of brevity. Instead, a summary of the system status is reviewed.

5.7.1 Risk Assessment

As discussed, sourcing a motor and the chain design were the critical design risks. These two elements of the system presented the most issues, as well. Field-testing conducted with POC-4 confirmed functionality of these systems. Therefore, there was a high level of confidence that all requirement thresholds would be achievable by the prototype.

5.7.2 System Costs

Usually, a significant amount of time is invested into managing cost. For this developmental effort, however, the funding available was known to be in excess of what was required. Of the $10,000 allotted, conservative estimates with significant risk allocations showed only $6,000 should be required. Also, ARSENL had already invested approximately $1,600 into the construction of POC-1 prior to the establishment of the $10,000 cap. Therefore, the net amount funded was $11,600. To date, $3,126.94 was invested into the development of POC-1 through POC-4. This left approximately $8,500 for prototype construction. The only significant change planned was the use of extruded aluminum for the frame. The estimate for this was approximately $1,500, ergo the budget was thought to be in excellent condition with a $7,000 buffer for unforeseen expenses.

5.7.3 TRL Assessment

POC-1 satisfied the requirements to establish the readiness level at TRL-2. This level is where invention begins, and basic principles are observed. The Defense Acquisition Guidebook (DAG) notes that applications at this level "are speculative and there may be no proof or detailed analysis to support the assumptions" [19].

POC-2 allowed for individual component experimentation to partially satisfy TRL-3. The types of tests that took place are characteristic of TRL-3, but the system still lacked the ability to validate analytical predictions that are required for TRL-3.

POC-3 validated the analytical models for TRL-3, and it also allowed the system to be tested at TRL-4. The primary characteristic of a system at TRL-4 is that components have been integrated and proven to work together. However, it is still "low fidelity" compared to the final product [19].

Full system testing of POC-4 in a relevant environment satisfied the requirements for TRL-5. To progress to TRL-6, the system required automated capabilities and sensors that were not yet coded into the control logic. For more information on these elements, refer to [22].

CHAPTER 6: Prototype Development

Referencing, for the last time, the systems engineering (SE) process shown in Figure 6.1, it was now time to build the prototype and validate it against system requirements. Prototype testing and validation would mark research completion.

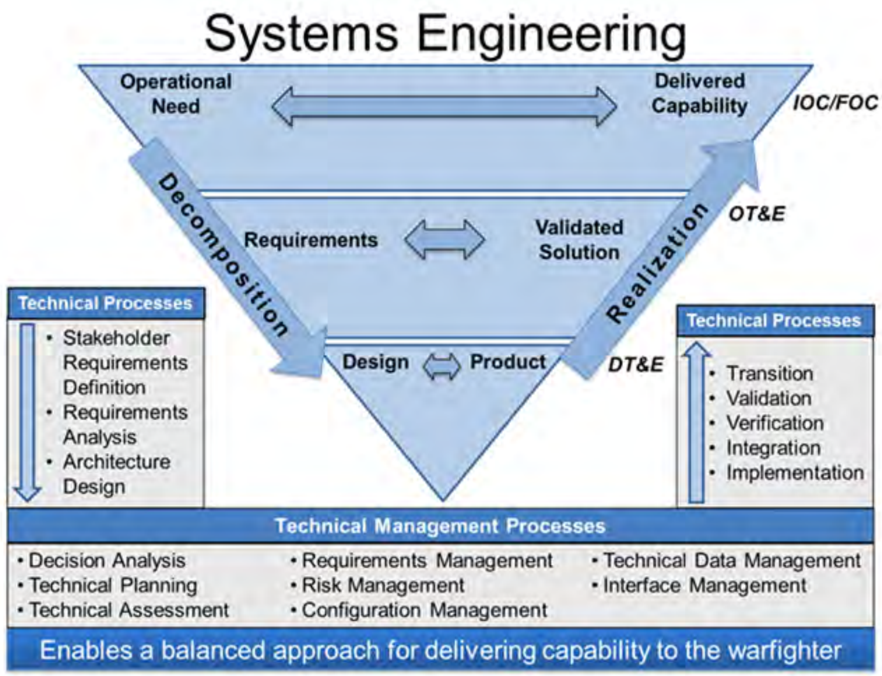

Figure 6.1: DOD SE Process Overview, from [19]

6.1 Overview

As a *jeu de mots* on the relatively high-current draw observed during proof-of-concept (POC) development, it was decided to name the prototype AMPPS. The acronym stood for "Automated, Multi-Plane Propulsion System."

The primary goal for AMPPS was to provide ARSENL with a solution that was suitable for long-term, operational testing. POC-4 had already demonstrated a functional baseline, what it lacked was any kind of environmental protection or structural durability. Also, provisions needed to be made for the integration of automated systems and sensors. This chapter presents an overview of what automated capabilities were added, but, as previously mentioned, these were not the focus of this study.

For chronological clarity, the computer-aided design (CAD) development for the prototype began shortly after the construction of POC-1. Schedule constraints required a design freeze and component ordering for the prototype to take place halfway through the testing of POC-4. At the time the order was placed, it was known that the motor selection was adequate, but the unmanned aerial vehicle (UAV) interface had not been tested. The original intent was to validate fully the proof-of-concept before investing in longevity for a system that was still unproven. For example, the one inch main bearings used for the concepts were approximately \$12 apiece. Bearings that met environmental requirements for being dust and water resistance were approximately \$85 apiece. Fortunately, the POC was successful and the investment worthwhile. However, this order of development is not recommended and, as will be shown, issues did arise as a result.

6.2 Structural Development

Lessons learned from the development of the RULE design suggested that extruded aluminum was an ideal choice for the framing material; therefore, this was selected for the structure. Top considerations for the structural layout were:

- Attention was given to minimizing the weight of the structure. Several methods were used to accomplish this goal, but the primary focus was on using elements of the structure for multiple purposes. For example, the mounting support for the wheel motors are sized to serve as the battery tray, too. This eliminates the need for extra supports just to mount the batteries.
- Sizing of the structure is designed to allow for component mounting without the need for custom adaptors. Various ways in which this is implemented will be discussed as the design is presented.
- The framing would be delivered cut to length by the manufacturer. However, spare, uncut stock was ordered for replacement or modifications. This material is delivered in 12-foot lengths that would have to be cut in-house. For this reason, dimensions of the launcher's structure are designed in one-inch increments. Without computer-

controlled machining, cutting a six-inch length of material is accomplished more easily than cutting a 6.125-inch section.

The framing overviews, along with major changes, are discussed first. This will be followed by an explanation of the features for the final iteration. Figure 6.2 shows an overview of the first evolution of the frame. Note the UAV support rails are reclined in the CAD to demonstrate that they could be collapsed for transportation. This is not their position for launching operations.

Figure 6.2: Prototype Frame (V1)

Changes incorporated for the second version were:

- Version 1 (V1) of the prototype was designed using extruded aluminum with a one inch cross-section. Due to the long center-span, the manufacturer recommended switching to larger, 1.5-inch framing for rigidity. This would be incorporated into V2.
- The wheel motors were originally mounted to the upper surface of the battery trays. With this configuration, however, the design was unable to fit through a standard doorway (R23). Therefore, the wheel motors were moved to the lower surface in order to reduce the width of the structure.
- The idler sprockets are arranged for a system that does not have attachments. This

means the chain can be supported from either side without an issue. Once attachments were added, the chain could only be supported from the inside of the circumference. Otherwise, the attachments would interfere the idler sprockets. This principle is shown in Figure 6.3

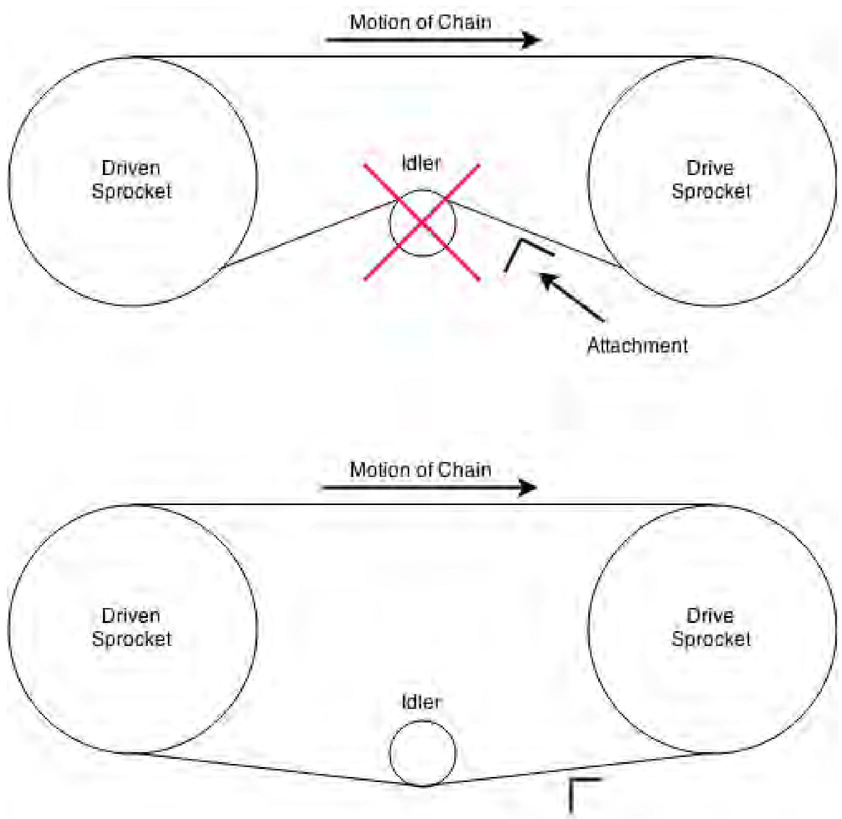

Figure 6.3: Attachment Binding with Idler Sprockets

The second version (V2) of the frame, is shown in Figure 6.4.

Features of V2 and the changes incorporated for the third and final version were:

- The manufacturer of the wheel motors indicated the motors could be configured as a direct-drive system. This version assumes the wheels would need to be mounted on separate shafts (to support the weight) and driven with a chain reduction.
- The height of the launcher is set at 40 inches as a human-factors consideration for loading UAVs. This height corresponds to an approximate average where the tech-

Figure 6.4: Prototype Frame (V2)

nician would not have to bend over to secure the UAV. The stakeholder indicated compactness was of greater concern than ergonomics; therefore, the height would be reduced in V3.

- An error by the author in transposing the battery dimensions resulted in inaccurate sizing for the CAD. They were actually much smaller, which allowed for new mounting locations in V3.
- The various sensors and electronics were originally planned to be located underneath the white plate used to mount the linear chain guide. The new battery location would allow for them to be mounted on trays where the batteries are shown in this version. This is a better location for minimizing the lengths of wire connections.

The third configuration (V3), which represents the design that was ordered, is shown in Figure 6.5. The specifics of this design are discussed in detail in the next section.

Figure 6.5: Prototype Frame (V3)

6.3 Structural Design Elements

The first design consideration was the dimensions of the center section used to support the roller chain assembly. The height was determined by the mounting pattern of the chosen main bearings. The width was driven by the availability of six-inch wide Lexan sheets used to support the linear chain guide. Length for the drive section was selected at 12 feet in accordance with chosen design specifications from the length sensitivity study. The height and width dependencies are shown in Figure 6.6.

To eliminate the need for conveyor-belt tensioners, the idler sprocket is mounted on vertical supports that permit up and down adjustments of the location. This allows for tension adjustment without the tensioners. Also, the incorporation of a metal frame means the structure's tolerances would be very precise. This removes the need for the angular adjustment afforded by the tensioners. As a result, the main bearings do not require adjustment; therefore, they were screwed directly into the threaded ends of the extruded aluminum. Finally, the removal of the tensioners mandated that the motor's position be adjustable to allow for

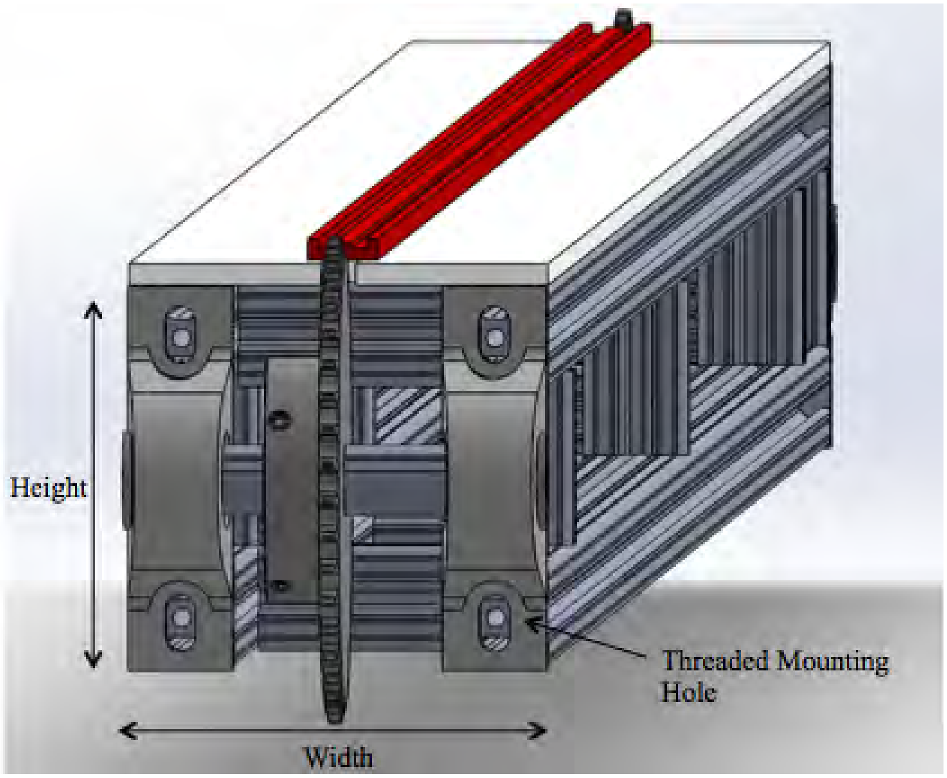

Figure 6.6: Prototype Drive Section

tensioning of the power transfer chain between the primary and secondary sprockets. This was accomplished by mounting a horizontal brace with enough width for adjustment. The motor mount is shown in Figure 6.7.

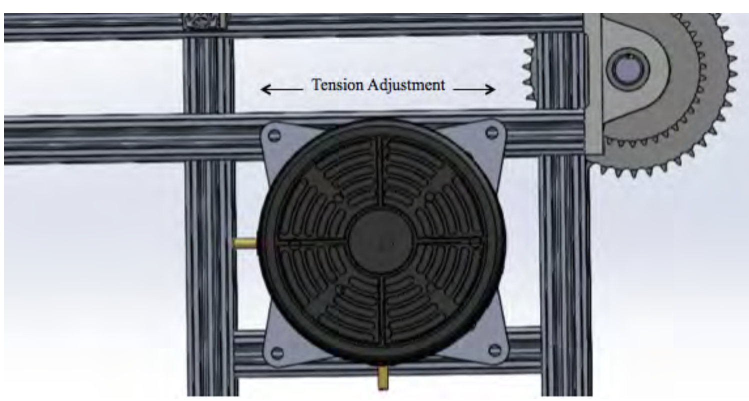

Figure 6.7: Prototype Motor Mount

Recall that the primary and secondary sprockets for the POC were located outside of the main bearings. To guard the chain assembly, and also to remove any torque generated by the tension of the power transfer chain, these are relocated inside the bearings as shown in Figure 6.8.

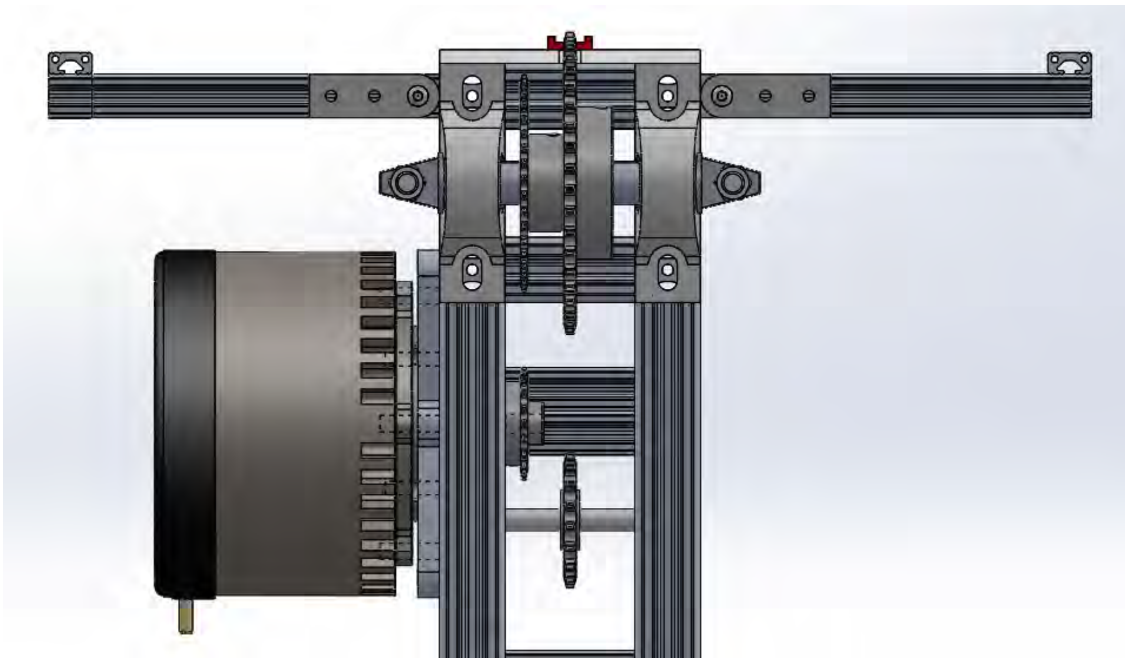

Figure 6.8: Prototype Sprocket Configuration

Finally, a standard U-bolt is added for user protection from the driven sprocket. It is also meant to serve as a capture device, should the main launcher chain break during operation. The application is shown in Figure 6.9.

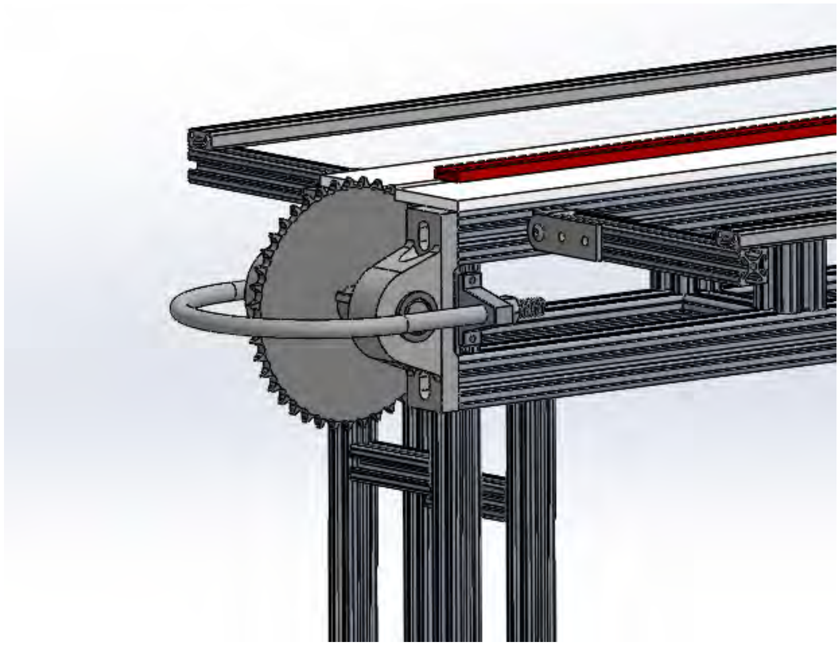

Figure 6.9: Prototype Chain Guard

6.4 Construction

While CAD is certainly a useful aid, there were limitations. For example, the structural rigidity of the aluminum framing could be calculated in CAD, but it was not a replacement for tactile feedback. Early in the construction process, it was noticed that the drive section assembly was over-engineered. Rigidity appeared to be far greater than what was necessary; therefore, the lower longerons were removed in the center section as shown in Figure 6.10. This modification removed 32 pounds of weight from the prototype without sacrificing functionality.

Another design change, shown in Figure 6.10, was the removal of a single tailwheel in favor of dual-castering tailwheels. This element was changed from the CAD for increased stability.

The next major alteration made during construction was the UAV support rails. Recall that the use of Velcro for the UAV nose hold-down required the support rails to contact the aircraft at the same longitudinal location as the interface. This was to prevent pitching of the UAV's nose during interface release. As a consequence of ordering the frame prior to

Figure 6.10: Prototype Removal of Lower Longeron

completing POC interface testing, modifications to the metal structure had to be made to reflect the requirement. To accomplish this, the support arms are cut down, and the rails are rotated on edge. This modification also provides an added benefit: it serves as a propeller guard during launch to prevent wind-milling. Figure 6.11 shows the original support rail location on the right, and the change (prior to cutting the support arm) on the left.

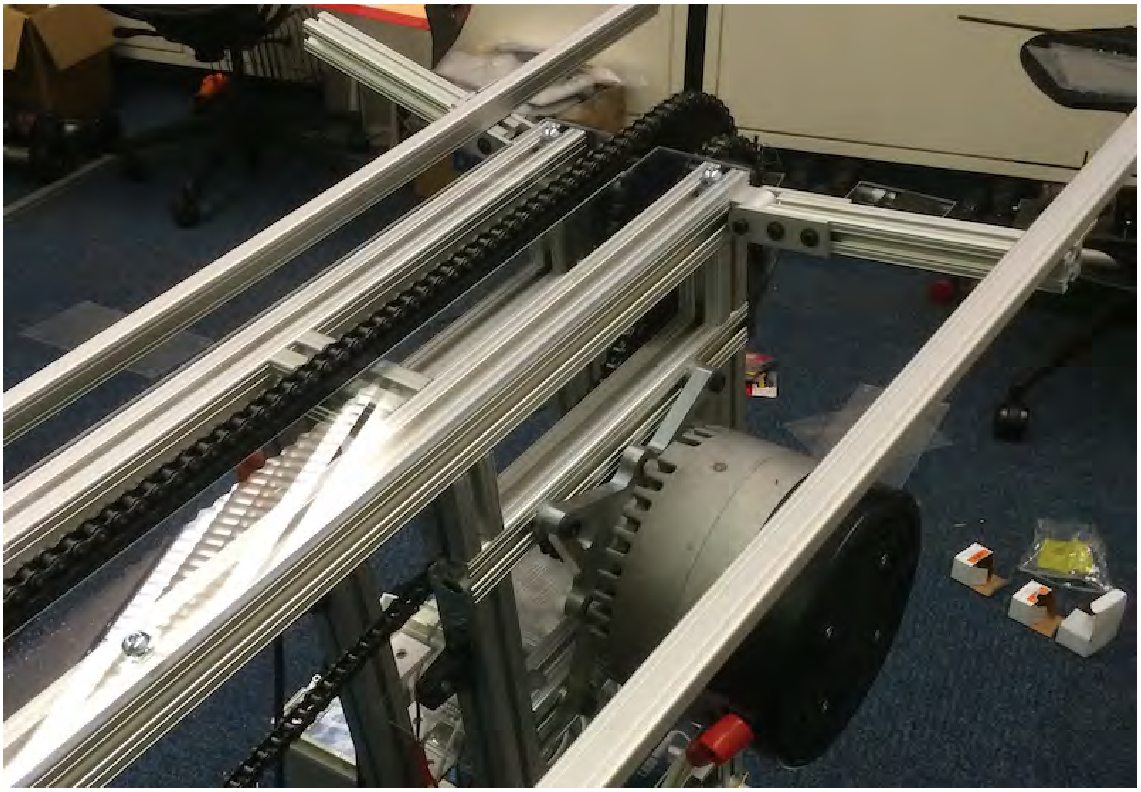

Figure 6.11: UAV Guide Rail Modification

To accept the required electrical suite, Lexan shelves are built into the front legs. Also, a power switch control panel is mounted to the rear UAV support rail arm. These features are shown in Figure 6.12 and Figure 6.13.

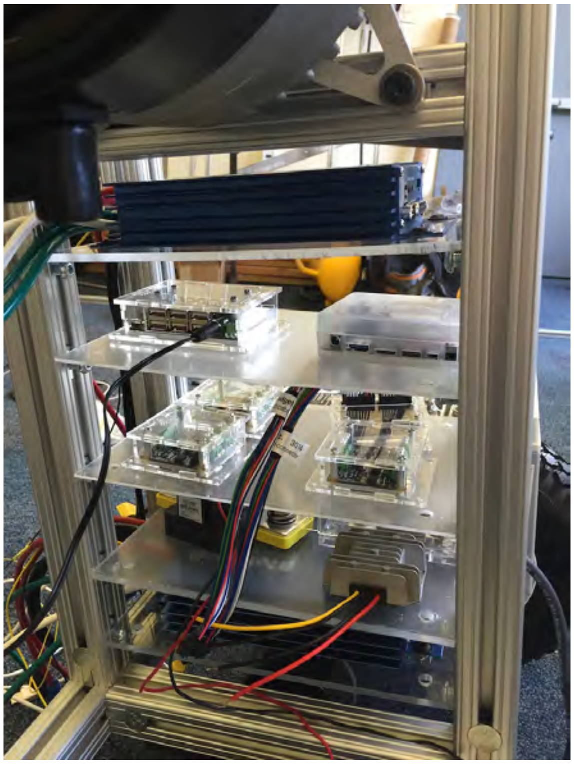

Figure 6.12: Lexan Shelving for Electronic Suite

Figure 6.13: Power Switch Control Panel

The final construction elements are shown in Figure 6.14. The last modification from the CAD was the relocation of the idler sprocket to the front-leg supports. This ensures clearance of the UAV interface wedge with the motor shaft, and also eliminates the need for extra mounting structure. Also shown is the 3-D printed mounting solution for the LCD information screen. The case, along with the UAV interface, are the only custom components on the system.

Figure 6.14: LCD Screen and Idler Sprocket Mount

6.5 Sensor Integration Overview

This author did not develop the sensory and electrical systems, but they are essential to the operation of the launcher. Therefore, an overview of the sensor suite and automated capabilities is required. For more detailed information on any of these sub-systems, refer to [22].

Wireless Operation

All commands (launch, slow-speed chain positioning, driving the wheel motors) are accomplished wirelessly via a Bluetooth controller. This allows for remote operation of the launcher during relocation and also standoff distance for the technician during launch. All functions require two-handed button combinations to reduce the likelihood of accidental command inputs.

Safety

The system has multiple fail-safes to ensure user safety. Starting with the electrical system, the battery bank is hard-wired into a manual On/Off switch. With this switch off, no power is available to any part of the system. Once the master switch is engaged, the control panel at the rear of the launcher is used to selectively provide power to the main motor speed controller, the wheel motor's speed controller, and the on-board microcomputer. These switches are hard-wired as well; therefore, no current can flow to the motors or computer with them in the off position.

Software-based logic in the speed controllers does not allow them to send commands to the motors without positive identification of the microcomputer. Should control signals be lost, the controllers defaulted to off. To prevent a runaway situation of any kind, a kill button is programmed into the wireless controller that electronically commands a main contactor to open. This cuts power to the entire battery array.

For launch safety, sonar sensors are mounted to the near and far end of the launcher. Launch commands are ignored if any object is detected within the programmed sensor range.

Launch Control

A highly-sophisticated speed controller manages the launcher's main motor. The motor does not contain hall sensors; thus, the RPM cannot be directly measured. For control, open-loop current limiting is used in combination with timing functions to produce linear throttle responses. The timing functions are commanded from a separate microcomputer on board the launcher. The same timing function is also utilized to automatically shut off power to the motor after a launch is complete.

Wheel Motor Control

A two-channel version of the main motor's speed controller is used to independently drive the wheel motors. Joystick commands received from the wireless controller are proportional for smooth steering and speed control when relocating the launcher.

Communication

Rapidly launching a high number of visually-identical UAVs makes aircraft identification difficult. To mitigate this, each aircraft is embedded with a radio-frequency identification (RFID) tag. To read the data, a RFID reader is mounted where the UAV is loaded for launch. The LCD screen displays the aircraft information for both the technician and the UAV's forward-looking camera.

To sense weather, the launcher wirelessly pulls data from a nearby weather station. On-board heading sensors allow for crosswind calculations. Though not implemented, this could later be used to alert the technician if the launcher were outside of cross-wind limitations for the UAV. Also, the system could be configured to automatically reposition into the wind.

A three-color light tower is mounted to the front-wheel supports for visual confirmation of system status. The lights are programmed to alert the technician of various system states. This includes any unsafe condition (such as tripped sonar sensors), pending launch command received, and ground control station (GCS)-down status. Also, an audible alert tone is programmed to sound three times, warning personnel in the area that a launch has been initiated.

6.6 Testing

The final round of testing was conducted in a relevant environment at the Advanced Robotic Systems Engineering Laboratory (ARSENL) testing facility. Recall that the stated Technical Readiness Level (TRL) goal for the prototype was to reach TRL-7. This readiness level requires an operational environment. To consider the environment operational as opposed to relevant, ARSENL would need to be conducting swarm mission sets. Scheduling conflicts did not allow for the launcher to be used for this purpose. Instead, the testing conducted for POC-4 was repeated, but with operational, untethered UAVs. Even though the same tests were conducted, the launcher now qualified as a "representative model or prototype system" to satisfy the definition of TRL-6.

The first day of testing revealed the critical UAV interface issue mentioned during POC-4 testing. All previous launch tests were conducted on ARSENL-constructed aircraft. The Zephyr II platforms used for this round of testing were built under contract by a third party. This was the first time these aircraft had been flown, and it was discovered that an inadequate amount of glue had been applied to the motor mount. As a result, the aluminum motor mount delaminated from the aircraft during the second launch attempt. This is shown in Figure 6.15.

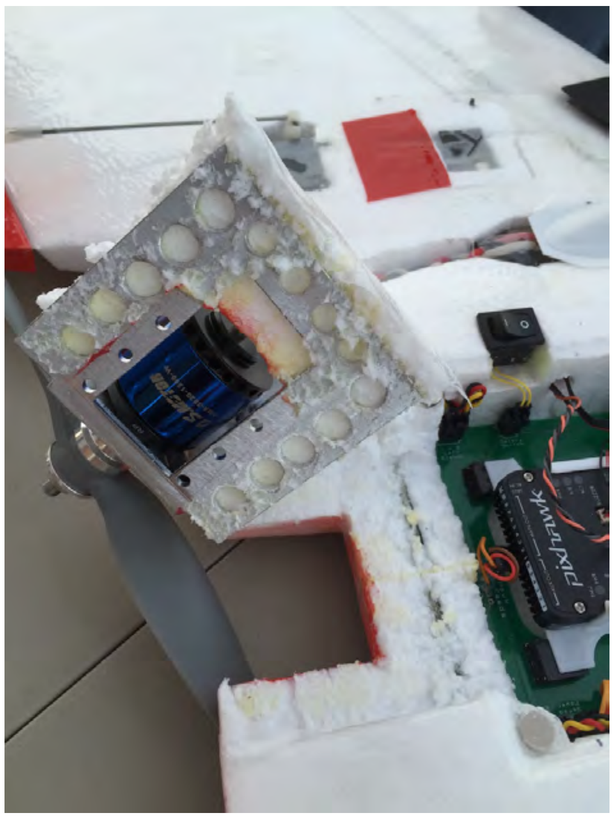

Figure 6.15: Delamination of Motor Mount

Although the fault was considered to be with the aircraft, 100 UAVs have already been ordered under the same contract. This element of the UAV's construction is difficult to strengthen post-build, necessitating an alteration to the launcher.

To avoid all contact with the motor mount, a solution needed to be developed rapidly in order to return to a nose-only UAV interface. The primary issue with previous attempts was the failure of the Velcro to hold during intial power application. This was attributed to its inability to absorb the shearing forces associated with rapid acelleration. To mitigate this issue, a hybrid of the previous design was conceived. A backing plate was integrated into the interface component that mounted to the roller chain. This is shown in blue, along with the white UAV interface, in Figure 6.16.

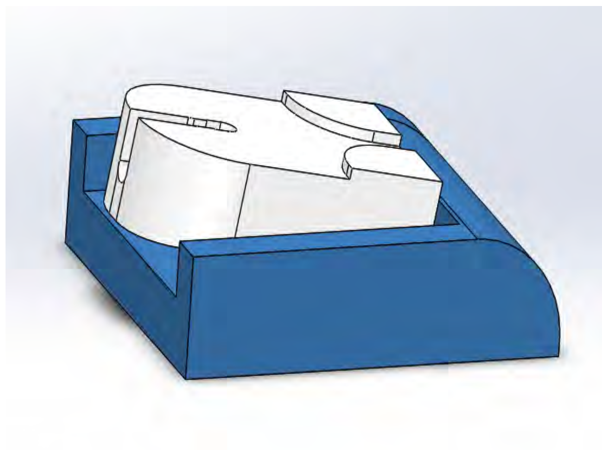

Figure 6.16: Captured UAV Interface Design

The concept was tested the next day, and 13 succesful launches were conducted using the new interface. Figure 6.17 shows the UAV immediately prior to launch.

Despite successful testing, the interface was not without issues. Repeated launches of the same aircraft showed that fatigue was occurring in the UAV launch hook. It began to flex under the load exerted during launch. The team determined more support structure was needed where the interface contacted the UAV. This would help to distribute the force. As it was, all forces were transmitted directly to the hook. Time did not permit the implementation of this change, but it was recorded and recommended for future work.

Figure 6.17: AMPPS System Testing at Camp Roberts, California

6.7 Results

The success of a system is measured by its ability to satisfy stated requirements. Some of these were referenced throughout the development, but a complete analysis is required for system validation. The requirements, along with tested results, are shown in Table 6.1.

Table 6.1: Final Testing Results

High-Level Requirements

Requirement Identifier	Measure Identifier	Measures	Units of Measure	Objective / Threshold	Tested Capability
R1	MOE 1	Launch Rate Performance	Number of Aircraft	>55 / 50	Not Tested
R2	MOE 2	System Availability	Setup Time (Minutes)	<13 / 15	5
R3	MOE 3	Launch Reliability	Number of Aircraft	<0.5 / 1	Needs Further Testing
R4	MOE 4	Wind Adaptability	Adjustment Time (Seconds)	<10 / 15	2
R5	FUN 1	Safety	True / False	True	True
R6	CON 1	Legacy Adaptability	True / False	True	True
R7	CON 2	Use of COTS Components	Number of Custom Components	<5	2
R8	CON 3	System Length	Length (Feet)	<16	12
R9	CON 4	Expense	U.S. Dollar	<$10,000	$6,346.59

Performance Requirements

Requirement Identifier	Measure Identifier	Measures	Units of Measure	Objective / Threshold	Tested Capability
R10	MOP 1	System Reset Time	Time Required to Reset Launcher	<5 / 8	4
R11	MOP 2	UAV Load Time	Time (Seconds)	<8 / 10	6
R12	MOP 3	Portability	Number of Personnel	<1 / 2	1
R13	MOP 4	Launch Velocity	Velocity (MPH)	>40 / 35	38

Functional Requirements

Requirement Identifier	Measure Identifier	Measures	Units of Measure	Objective / Threshold	Tested Capability
R14	FUN 2	Environmental Sensing	True / False	True	True
R15	FUN 4	System Communication Capability with UAV	True / False	True	True
R16	FUN 5	UAV Attachment Capability	True / False	True	True
R17	FUN 6	UAV Detachment Capability	True / False	True	True

Constraint Requirements

Requirement Identifier	Measure Identifier	Measures	Units of Measure	Objective / Threshold	Tested Capability
R18	CON 5	System Adaptability with UAV	Force (Pounds Force)	>20	15
R19	CON 6	Number of Technicians Required to Load a UAV	Number of Technicians	<2	1
R20	CON 7	System Tie-Down Adaptability	True / False	True	True
R21	CON 8	Environmental Survivability	True / False	True	True
R22	CON 9	Environmental Survivability	True / False	True	True
R23	CON 10	Maximum Width For All Orientations	Width (Inches)	<35	32
R24	CON 11	System Weight	Weight (Pounds Mass)	<80	N/A
R25	CON 12	System Weight	Weight (Pounds Mass)	<160	N/A
R26	CON 13	System Weight	Weight (Pounds Mass)	<500	245/True
R27	CON 14	Number of Launchers Required to Accomplish Launching Mission	Number of Launchers	<2	True

AMPPS was able to meet or exceed all requirement thresholds with the exception of two, for which testing is pending. Requirement 1 (R1) stated that the system “shall be capable of launching 50 aircraft within 15 minutes.” ARSENL’s swarm size was not yet large enough to facilitate a 50-aircraft launch; therefore, this metric could not be tested. However, the system was tested for UAV load times (R11) and system reset time (R10). The total time consumed for these two tasks should amount to the launch interval time. If this holds true, the system is capable of launching an aircraft every 12 seconds – or 75 aircraft in a 15-minute window – thereby satisfying (R1).

The second untested measure is related to the launcher’s reliability (R3). Time constraints prevented the 100 required launches from being conducted. However, the new UAV interface worked with no launching failures; ergo, the system was on-track to accomplish the threshold for this requirement.

CHAPTER 7: Conclusion

7.1 Summary of Findings

The research goal was to design and build a working unmanned aerial vehicle (UAV) launcher prototype that met all cost, schedule, and performance requirements for the ARSENL team. From beginning to end, SE practices were utilized as the framework. The core benefit afforded through the use of systems engineering (SE) is that it provided the necessary tools and techniques to make informed decisions throughout the process.

The methodical approach to system decomposition allowed the author to fully define a set of requirements that would satisfy the operational need. This process was essential to the development because it defined precisely what the prototype must "do" to provide value to the stakeholders. In complex systems, it is easy to inadvertently overlook requirements that, if omitted, would render the solution useless. The decomposition process was used to holistically evaluate a total system solution in order to minimize the likelihood of this occurring. Key findings observed during this process were:

- Stakeholder preferences, at times, were difficult to interpret. Sometimes, the stated need cannot be directly transferred into a requirement. For example, Advanced Robotic Systems Engineering Laboratory (ARSENL) requested a launching solution that would support their goal of 50 UAVs simultaneously airborne. It was the responsibility of the development team to determine performance parameters (50 aircraft in 15 minutes) that would satisfy that need. This requirement was the result of analyzing UAV endurance and desired combat duration.
- In other instances, the stated need is not the best solution. For this research, the stakeholders were also the end-users. The focus point for an end-user is typically the performance parameters that are lacking from their current system. For example, during the development of the RULE launcher, it took ARSENL five to ten minutes to launch each UAV. They attributed the long cycle time to the bungee launcher, but, upon observation of the operations, it became clear that procedural inefficiencies

during UAV staging were actually the source of delayed launch intervals. The capstone team recommended changes that resulted in the one-to 1.5-minute cycle time quoted at the beginning of this research. It is the job of the SE team to analyze the stated need and determine the correct course of action from a holistic point of view. This cannot be accomplished without a full, top-down decomposition of all aspects affecting the system.

Once an understanding of the system requirements was established, a market analysis was conducted to determine if an existing system was capable of meeting said requirements. Also, this process was utilized to establish industry design standards that could be applied to the development effort. Results indicated that a unique solution was warranted, so the design process commenced. The major takeaway from this phase of the SE process was:

- Market analysis is a requirement for Department of Defense (DOD) acquisition programs [19]. However, it is an easy process to eliminate for personal, or small-scale, design efforts. The importance, however, cannot be overstated. Even in instances where suitable solutions for this research were not found, the process of thoroughly researching existing systems was crucial to the concept development stage. It can sometimes be difficult to accurately trace the specific source of information used to make a decision. Generally, engineering decisions are based on experience and data. Market analysis provided the experience – and the data – required to inform many of the concept decisions.

Concept generation and design selection were accomplished by evaluating the proposed system against stated requirements and build feasibility. The limited manufacturing and construction capabilities of the small development team had to be taken into account when selecting a concept. Based on these considerations, a belt-driven, electrically powered solution was selected.

- A realistic self-evaluation was critical to this phase of development. It was important to factor into the process, schedule and team limitations. Even for large engineering firms, the solution has to be tailored to the capabilities of the firm. Unlimited funding can accelerate schedules, but technological barriers that even additional funding cannot overcome still exist.

Next, design goals were established and evaluated using TRL definitions. Also, a risk management plan was generated to help determine the order of technological progression. High-risk, critical systems were developed first, followed by the integration of less essential sub-systems. The progressive introduction of technology was accomplished through iterative prototyping. This construction method allowed for rapid design changes not only to address current issues but also mitigate future risk concerns.

- Risk was among the most difficult aspects of development to identify and manage. The did not in any way anticipate the amount of effort that would be required while working on the UAV interface. It was identified as a top-level risk, but the difficulty of the process was inadequately assessed. The result, restated in the following bullet, was unwarranted confidence in a critical sub-system that later rendered the entire system unusable.
- Assigning a Technical Readiness Level (TRL) to the system was also highly subjective. This goes hand-in-hand with risk and development prioritization. For example, at the completion of POC-4 (see Section 5.6), the team determined that the UAV interface was at a higher readiness level than was actually the case. This resulted in last-minute design changes just to complete the final phase of testing.

Throughout the prototyping process, the suitability of the system was continuously assessed. This was accomplished through the use of developmental test and evaluation (DT&E). The purpose of the tests was to evaluate the current TRL, and determine the status of perceived risks as they evolved. Also, the tests were used to verify that the design solution was meeting system requirements. These findings were critical to making informed decisions about the direction of the desired prototype evolution as the research moved forward.

- Focusing again on the UAV interface, the importance of testing in *relevant* environments became apparent and circles back to assigning the correct TRL. POC-4 was assigned at TRL-5, which requires a relevant environment. However, the UAV used for this test was not representative of an operational UAV. This easily missed, minor difference between the two aircraft rendered the system unusable on the first day of final testing.
- Given schedule constraints, simultaneous development of sub-systems was required.

This is not an unusual practice for engineering projects. However, the efficiency gained from this method can be entirely lost if communication breaks down between development teams. It has been mentioned that the team for this development was only two individuals, representing mechanical and electrical leads. However, communication was still essential among the team members. Many design decisions made from a mechanical perspective had an impact on the electrical side, and vice-versa.

At the completion of prototype construction, the final stage of developmental tests and evaluations were conducted at the ARSENL testing facility. The Automated Multi-Plane Propulsion System (AMPPS) solution either met, or was predicted to meet, all requirements established at the beginning of the design process. It was established at a TRL of 6, and technological risks had been minimized. The solution was delivered on time and under budget. The success of the system was directly attributed to the team's adherence to using established SE practices from research conception to completion. Concluding findings were:

- As mentioned, the prototype was delivered on-time. However, it was expensive to correct design issues that arose late in the development process. Several components had to be shipped overnight to remain on schedule. The ordering process was such that packages would arrive anywhere between one week and one month later. Shipping delays – or supply-chain logistics for large-scale operations – can have a negative impact on every aspect of development. In addition to schedule slips, there were times when testing could not be performed while the team was waiting for delivery of a component. However, the design effort had to continue; therefore, decisions were made based on incomplete testing results. One example of this was the requirement to order a speed controller before the shunt arrived to measure amp-flow in the system. The team spent approximately $600 on a controller that did not work. Fortunately, funding was available to help mitigate these issues, but that is not always the case (nor is it a best-practice approach).
- During design and construction, it was easy to underestimate the time required to perform the "simple" tasks. It was later discovered that nothing is simple until it is complete. Focusing on the perceived major tasks and leaving trivial items for last is

likely to result in an unfinished solution.

- As observed during the RULE launcher development, the AMPPS prototype was capable of cycle times that far exceeded the UAV staging procedure used by ARSENL. Mechanical limitations of the launcher were no longer the choke point in the operational flow. Further automation of the staging process will be required to fully utilize AMMPS's cycle-time performance.
- The launcher was mostly operated by the development team during testing. Occasionally, a member from ARSENL would load the UAV or command a launch from the wireless controller. It was interesting to note that, what seemed intuitive to the design team was not necessarily intuitive to the user. The importance of end-user feedback throughout the design process was realized.

7.2 Recommendations for Future Work

The work outlined in this study is only a starting point for exploring launcher technologies related to swarming UAVs. This field of study is in its infancy, and would greatly benefit from future research. Beyond the mechanical design of launching systems, there are multiple contributing factors that affect launching performance. Some of the high-level aspects to consider are:

System of Systems Integration It is highly probable that these launching systems will eventually be deployed aboard ships, surface vehicles, and perhaps other aircraft. The integration of these systems into highly complex, mobile platforms presents an entirely new set of challenges to overcome. Studies should be performed that explore the changes in manning requirements, Concept of Operations (CONOPS), effects on war fighting capabilities, supportability, and survivability, to name a few.

Human Factor Considerations Conceivably, the continued development of advanced autonomy will one day permit a single technician to control hundreds, or even thousands, of UAVs. If this capability is realized, the launching systems used to deploy these units will require the same level of autonomy. This also applies to the recovery of swarms.

CONOPS The necessity to study ground-crew operations is closely linked to the required automation of launch and recovery systems. As was seen in the CONOPS of ARSENL, the material solution was no longer a limiting factor. If taking full advantage of the afforded cycle rate using the AMPPS solution is desired, further study will be required to evaluate crew processes and optimize efficiency.

Specifically for the AMPPS prototype, there are several areas of work that deserve continued study. Primarily, the system would benefit from continued prototype development and testing in an operational environment. The areas of focus should be:

Weight Reduction The materials chosen for construction were readily available and easy to construct. Once the system matures beyond the prototype stage, there would be great value in exploring advanced manufacturing techniques to reduce weight. For example, changing the framing material from aluminum to a composite structure like carbon fiber would reduce the weight by more than 100 pounds. This was briefly considered as an option during prototype development, and would cost approximately $1500 to implement.

Multiple Platform Compatibility Currently, the UAV interface design is only capable of launching a Zephyr II UAV. However, modifying the interface to contact points that are common to most aircraft (for example, the trailing edge of a wing) would greatly contribute to the versatility of the system.

Supporting Systems The system demonstrated a launch cycle time of 12 seconds. Eight seconds were devoted to the human element of loading the UAV for launch. Performance could be further enhanced through the development of an automated loading system for the UAVs. Conceivably, this could be realized through the addition of a hopper-type attachment. Such a device would reduce cycle times and relieve technician workload.

Continued Testing Time constraints limited the amount of testing that could be performed. Little is known about the long-term survivability of the system. Continued testing should be targeted to determine the reliability, probable modes of failure, maintainability, and performance degradation over time.

APPENDIX: AMPPS Bill of Materials

Table 1: AMPPS Mechanical Bill of Materials

Item	Vendor	Part Number	Unit Cost	Quantity	Total Cost
1/2" Shaft Base Mount	McMaster	185K3	$17.40	2	$34.80
1/2" Steel Drive Shaft	McMaster	1346K19	$23.53	1	$23.53
Collar Clamp	McMaster	6435K14	$2.11	4	$8.44
1/4" Key Stock	McMaster	98535A450	$11.10	2	$22.20
ANSI 40 Idler Sprockets	McMaster	6663K41	$28.78	2	$57.56
ANSI 40 Roller Chain	McMaster	6261K173	$90.80	1	$90.80
Connecting link for ANSI No. 35 Roller Chain	McMaster	6261K191	$0.82	2	$1.64
Connecting link for ANSI No. 40 Roller Chain	McMaster	6261K193	$0.87	2	$1.74
Horizontal tab attachment link for ANSI 40	McMaster	7321K7	$2.94	3	$8.82
Shoulder Screw for Japanese Bearings	McMaster	91259A709	$1.97	8	$15.76
Mount Tabs for Wheel Motors	McMaster	47065T155	$1.79	8	$14.32
Wheel motor mount bolts	McMaster	47065T234	$1.58	4	$6.32
Extra Concealed Fasteners	McMaster	47065T156	1.91	12	$22.92
Switch Panel	McMaster	8560K239	8.63	1	$8.63
Extra Anchor Fasteners	McMaster	47065T154	3.89	10	$38.90
Sheet for linear guide	McMaster	8589K64	$42.50	1	$42.50
Linear Guide	McMaster	93095K5	$30.96	3	$92.88
Shelving Supports	McMaster	47065T224	$4.06	24	$97.44
Screws to mount Shelves	McMaster	90909A532	$11.69	3	$35.07
Nuts for shelf screws	McMaster	92673A119	$5.86	1	$5.86
Spare Nuts	McMaster	92673A113	$3.79	1	$3.79
U-Bolt Guard	McMaster	3043T4	$6.97	1	$6.97
Primary Sprocket	McMaster	2500T48	$22.34	1	$22.34
80/20 Frame	GA Worth Company		$1,187.59	1	$1,187.59
7" Main Drive Sprockets	McMaster	6236K14	$60.50	2	$121.00
Pneumatic Caster Wheel	Uline	H-3328BL-SWB	$49.00	2	$98.00
Motor mount and pillow bearing mounting screws	McMaster	91259A619	$1.27	12	$15.24
Motor mount and U-Bolt guard mounting hardware	McMaster	47065T229	$1.46	8	$11.68
Main Sprocket Drive Shaft	McMaster	8488T83	$27.10	2	$54.20
Battery terminal cover (black)	McMaster	69875K94	$2.00	5	$10.00
Battery terminal cover (red)	McMaster	69875K94	$2.00	5	$10.00
Roller chain guide	McMaster	93095K18	$188.64	1	$188.64
U-Bolt mount	McMaster	6068K23	$25.99	2	$51.98
Plane guide UHMW tape	McMaster	7344A24	$8.03	2	$16.06
ANSI 40 Roller Chain	McMaster	6261K173	$45.40	1	$45.40
Fastening tabs for 15 Series Extruded Aluminum	McMaster	47065T229	$1.46	60	$87.60
End Caps for 10 Series Extruded Aluminum	McMaster	47065T91	$1.20	10	$12.00
End Caps for 15 Series Extruded Aluminum	McMaster	47065T87	$1.50	4	$6.00
1" Pillow Mount Bearings	McMaster	5057N1	$82.14	4	$328.56
Wheel Adaptor Plate	Robot Marketplace	NPC-PH448	$20.00	2	$40.00
14" Flat Proof Wheel	Robot Marketplace	NPC-PT5306	$87.94	2	$175.88
Roller Chain Guide Tape	McMaster	76675A23	$36.53	1	$36.53
Secondary Sprocket	McMaster	2500T62	$57.24	1	$57.24
Scotch Extreme 1" x 3" Black Strip	Home Depot	051131642546	$3.57	1	$3.57
Loctite 242 Blue Threadlocker	Home Depot	079340242005	$6.47	1	$6.47
0.22in thick, 18x24 in Acrylic Sheet	Home Depot	769125020316	$19.97	1	$19.97
0.093in thick, 18x24 in Acrylic Sheet	Home Depot	769125010515	$9.78	4	$39.12
Adjustable Flag Bracket	Home Depot	792723402253	$6.97	1	$6.97
			Total Mechanical Cost		$3,292.93

Table 2: AMPPS Electrical Bill of Materials

Item	Vendor	Part Number	Unit Cost	Quantity	Total Cost
48V DC Main Drive Motor	ElectricMotorsport	Motenergy EMC-R-LS	$525.00	1	$525.00
AmpFlow Wheel Motor	AmpFlow	W43-500-SR-10B	$498.00	2	$996.00
12V, 22Ah Battery	Amazon	XP750	$99.99	4	$399.96
ANL Fuse Holder	Amazon	EWFH	$6.05	1	$6.05
Manual ON/OFF Switch	Amazon	68180	$35.30	1	$35.30
8AWG Connectors for Wheel Motors	McMaster	8026K2	$3.38	8	$27.04
8AWG Ring Terminals	McMaster	7113K223	$9.09	1	$9.09
Keeper 8ft x 1in Lashing Strap (2 pack)	homedepot.com	85243	$7.97	1	$7.97
RoboteQ HDC2450 Brushed DC Motor Controller, Dual Channel, 150A, 50V, Encoder in, USB, CAN	roboteq.com	HDC2450	$645.00	1	$645.00
Hook-Up Wire - Assortment (Solid Core, 22 AWG)	sparkfun.com	PRT-11367 RoHS	$16.95	1	$16.95
XS Power 580 Short Battery Post Adapters M6	sonicelectronix.com	XS Power 580	$10.99	4	$43.96
Bussmann ANN Very Fast-Acting Current Limiters ANN300	summitracing.com	BSS-ANN300	$27.97	1	$27.97
Roboteq HDC2460S Brushed DC Motor Controller, Single Channel, 300A, 60V, Encoder in USB	roboteq.com	HDC2460S	$660.00	1	$660.00
Harsh Environment High-Amp Distribution Bar - 1 Circuit, 250 Amps @ 300 VAC, 4 Stud Terminals	mcmaster.com	9290T17	$44.14	4	$176.56
Clear Cover for 9290T17 Harsh Environment High-Amp Distribution Bar	mcmaster.com	9290T29	$28.58	4	$114.32
Standard Ring Terminal - Vinyl Insulated, 22-18 AWG, 3/8" Screw/Stud Size	mcmaster.com	7113K614	$11.74	2	$23.48
Gigavac GXNC14CB Normally Closed 350+ Amp 12-800 Vdc Contactor with 24 Vdc Coil	Gigivac	GXNC14CB	$156.00	1	$156.00
Standard Heat-Shrink Ring Terminal8 AWG Wire Size, 3/8" Screw/Stud Size	mcmaster.com	7036K74	$11.36	5	$56.80
Standard Heat-Shrink Ring Terminal22-18 AWG Wire Size, 3/8" Screw/Stud Size	mcmaster.com	7036K63	$7.06	3	$21.18
Standard Ring TerminalVinyl Insulated, 8 AWG, 1/2" Screw/Stud Size	mcmaster.com	7113K716	$6.50	1	$6.50
Ultra-Flexible Wire 8 Gauge, Black, 10 ft long	mcmaster.com	7479K13	$35.80	2	$71.60
45 Feet, 18 AWG stranded wire (three 15 ft rolls)	Radio Shack	2781226	$7.99	5	$39.95
SPST Rocker Switch	Radio Shack	2750690	$3.49	3	$10.47
Noco 4 Channel Genius Charger	Amazon	B003JSLWWA	$320.95	1	$320.95
T-Slot Cover, 6' Long for 1-1/2" High Aluminum T-Slotted Framing Extrusion	mcmaster.com	47065T4	$4.27	3	$12.81
DROK 10A/50W 9-32V 12V/24V to 5V Car DC Voltage Converter Regulator Power Supply, Waterproof	Amazon.com	-	$15.49	1	$15.49
				Total Electrical Cost	$4,426.40

Table 3: AMPPS Sensory Bill of Materials

Item	Vendor	Part Number	Unit Cost	Quantity	Total Cost
3652_0 - LCD Screen 2x20 - LCM2002J	phidgets.com	3652_0	$25.00	1	$25.00
1204_0 - PhidgetTextLCD Adapter	phidgets.com	1204_0	$65.00	1	$65.00
1019_1 - PhidgetInterfaceKit 8/8/8 with 6 Port USB Hub	phidgets.com	1019_1	$125.00	1	$125.00
3919_0 - T5577 RFID Tag - PVC Disc 15mm	phidgets.com	3919_0	$1.35	30	$40.50
1024_0 - PhidgetRFID Read-Write	phidgets.com	1024_0	$60.00	1	$60.00
1128_0 - MaxBotix EZ-1 Sonar Sensor	phidgets.com	1128_0	$35.00	2	$70.00
1042_0 - PhidgetSpatial 3/3/3 Basic	phidgets.com	1042_0	$70.00	1	$70.00
3053_0 - Dual SSR Relay Board	phidgets.com	3053_0	$30.00	3	$90.00
3819_0 - Acrylic Enclosure for the 1204	phidgets.com	3819_0	$8.00	1	$8.00
3825_0 - Acrylic Enclosure for the 1024	phidgets.com	3825_0	$8.50	1	$8.50
3822_1 - Acrylic Enclosure for the 3053	phidgets.com	3822_1	$8.00	3	$24.00
3851_0 - Plastic Shell Enclosure for Spatials	phidgets.com	3851_0	$5.00	1	$5.00
Odroid-XU3	ameridroid.com	Odroid-XU3	$179.95	1	$179.95
DC Plug and Cable Assembly 5.5mm	ameridroid.com	DC Plug and Cable	$1.45	1	$1.45
AC/DC 24V Red Green Yellow LED Lamp Industrial Tower Signal Light	amazon.com	a11080800ux0057	$39.84	1	$39.84
RTC Battery	ameridroid.com	RTC Battery	$11.17	1	$11.17
3824_0 - Acrylic Enclosure for the 1019	phidgets.com	3824_0	$10.00	1	$10.00
SanDisk Extreme Plus 32GB UHS-I/ U3 Micro SDHC Memory Card Up To 80MB/s With Adapter	amazon.com	SDSDQX-032G-AFFP-A	$34.48	1	$34.48
Monoprice 15-Feet USB 2.0 A Male to Mini-B 5pin Male 28/24AWG Cable with Ferrite Core (Gold Plated), White	Amazon.com	108636	$5.94	1	$5.94
Logitech Gamepad F710 by Logitech	amazon.com	F710	$38.48	1	$38.48
			Total Sensors/CPU Cost		$912.31

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